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PROCEEDINGS OF
THE AMERICAN SOCIETY
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CONTENTS

Urbanization and Water Supplies for Northeastern Colorado
by Robert R. Smith 1

Changing Objectives: Chicago Metro Floodwater Plan
by Frank L. Kudrna and Roger K. Olson 13

Bureau of Reclamation Planning: Environmental Factors
by James E. Price and Leonard Ortolano 27

Planning for Drought: A Management Perspective
by James E. Crews 45

Computer Model for Small-Scale Hydropower Policy Analysis
by Paul H. Kirshen and Jeffrey S. Amlin 61

NAWDEX: Focal Point for Water Data Information
by Melvin D. Edwards 77

Residential Water Conservation
by J. Ernest Flack 85

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Cooperative Weather Modification Program
by John T. Carr, Jr. 97

Status of Southeast River Basin Water Resources
by Clair P. Guess, Jr. 105

Citizen Groups and Environmental Goals
by David S. Froehlich 113

Lake Michigan Diversion for Water Quality Control
by James W. Male and Karim Soliman 121

New Approaches to Water Utility Planning
by Alan K. Rowe and Daniel K. Sander 139

Urban Stormwater Management in Southeast
by David H. Howells and Neil S. Grigg 149

Sampling to Characterize Stream Plumes
by Christopher C. Clarkson, James W. Male, and Donald Dean Adrian 167

Growth Concerns Defeat a County Water Issue
by Charles H. Lawrance 183

Risk Avoidance Objective in Water Resources
by Ata M. Nazar, Warren A. Hall, and Maurice L. Albertson 201

WRC Standard Flood Frequency Guidelines
by Donald R. Jackson 211

Perspectives on Water Conservation
by the Task Committee on Water Conservation of the Water Resources Planning Committee of the Water Resources Planning and Management Division 225

Conversational Water Quality Data Retrieval System
by Douglas W. Larson and Thomas Bingham 239

Reducing Hydrologic Parameter Uncertainty
by Yeou-Koung Tung and Larry W. Mays 245

River Quality Model for Urban Stormwater Impacts
by Miguel A. Medina, Jr., Wayne C. Huber, James P. Heaney, and Richard Field 263

TECHNICAL NOTES

Proc. Paper 16072

Improved Hourly Reservoir Operation Model
by Leonard Becker and William W.-G. Yeh 283

DISCUSSION

Proc. Paper 16071

Two Centuries of Water Planning Methodology,* by Ray K. Linsley (Mar., 1979).
by Ellis L. Armstrong 291

Water Resources Planning—Historical Development, by Theodore M. Schad (Mar., 1979. Prior Discussions: Mar., 1980).
closure 293

Western Economic Development and Water Planning: Bureau of Reclamation,* by John E. Keith, Keith Wilde, Jay C. Andersen, and Allen LeBaron (Mar., 1979).
by Ellis L. Armstrong 294

Evaluation of Alternative Stormwater Detention Policies,* by Gregory E. Kamedulski and Richard H. McCuen (Sept., 1979. Prior Discussion: July, 1980).
by James S. Jenks 296

Map Skew???,* by Richard H. McCuen (Sept., 1979).
by Krishan P. Singh 298

Water Supply Regionalization: A Critical Evaluation, by Robert M. Clark (Sept., 1979. Prior Discussion: July, 1980).
closure 300

Voter Reaction to Multiple-Use Drainage Projects, by Thomas N. Debo and James T. Williams (Sept., 1979. Prior Discussion: July, 1980).
closure 301

*Discussion period closed for this paper. Any other discussion received during this discussion period will be published in subsequent Journals.

Water Resources Education Requirements of Engineering Firm, by Alan H. Schultz and Richard A. Westmore (Sept., 1979. Prior Discussion: July, 1980).
closure 301

Practical Aspects of Town Water Planning, by Paul G. Fischer and Tsung Ting Chiang (Mar., 1980).
errata 302

INFORMATION RETRIEVAL

The key words, abstract, and reference "cards" for each article in this Journal represent part of the ASCE participation in the EJC information retrieval plan. The retrieval data are placed herein so that each can be cut out, placed on a 3 × 5 card and given an accession number for the user's file. The accession number is then entered on key word cards so that the user can subsequently match key words to choose the articles he wishes. Details of this program were given in an August, 1962 article in CIVIL ENGINEERING, reprints of which are available on request to ASCE headquarters.

16091 NORTHEASTERN COLORADO WATER SUPPLIES

KEY WORDS: Colorado; Irrigation; Population; Urban areas; Urban development; **Urbanization; Water distribution; Water resources management; Water supplies;** Water supply systems

ABSTRACT: Increasing populations in Northeastern Colorado have resulted in reductions in irrigated acreage and the proportionate quantities of water available to support that segment of the agricultural industry. The growth has caused increased demands for municipal-domestic and industrial water supplies from the South Platte and Colorado River Basins. These impacts have been determined by comparing hydrologic data in conjunction with water use for agricultural, municipal-domestic, and industrial purposes between the period 1975-1979. Pricing and water rights ownership were also compared for the same period, as were land conversion data, population data, and crop production valuation. Proper administration of nonconsumptive return flows coupled with the importation of water from the Colorado River Basin will provide adequate, industrial, and irrigation water supplies for this growth intense area and downstream farm lands.

REFERENCE: Smith, Robert R., "Urbanization and Water Supplies for Northeastern Colorado," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16091**, March, 1981, pp. 1-11

16111 CHICAGO METRO FLOODWATER MANAGEMENT

KEY WORDS: Chicago; Erosion; **Flood control; Floodwater;** Government agencies; Project management; Project planning; Regulation; Reservoirs; Urban areas; **Water resources management**

ABSTRACT: Within the Chicago metropolitan area there was an urgent need to formulate floodwater management plans which would be accepted by local citizens and agencies and also satisfy requirements for Federal participation in implementation. The process was one of establishing watershed steering committees with close citizen, community and agency involvement from a grassroots level. Technical assistance was provided by the U.S. Department of Agriculture, Soil Conservation Service and local sponsors. The process encouraged formulation of plans that contained a unique balance of structural and nonstructural elements which merged into a comprehensive plan with broad-based support. Structural measures ranged from excavated reservoir and dike and channel improvements to modifications of existing structures.

REFERENCE: Kudrna, Frank L., and Olson, Roger K., "Changing Objectives: Chicago Metro Floodwater Plan," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16111**, March, 1981, pp. 13-25

16083 BUREAU OF RECLAMATION PLANNING

KEY WORDS: **Bureau of Reclamation; Environmental factors; Environmental planning;** Environmental quality; **Government agencies;** Multidisciplinary teams; **Natural resources;** Project planning; **Water resources**

ABSTRACT: The Bureau of Reclamation is a Federal agency responsible for planning and implementing multipurpose water resources development in the 17 western states. The results are reported of a research project that focused on the indentification of the practices and procedures through which planners have been the most effective in increasing the consideration given to environmental concerns. Past research was used to form testable hypotheses that relate the influence of environmental information on the outcomes of bureau planning investigations. Data for hypothesis testing was gathered through in-depth interviews with Bureau planning leaders and environmental specialists on 29 recent planning investigations. Results indicate statistically significant correlations between the influence of environmental information on planning outcomes.

REFERENCE: Price, James E., and Ortolano, Leonard, "Bureau of Reclamation Planning: Environmental Factors," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16083**, March, 1981, pp. 27-43

16078 MANAGEMENT AND DROUGHT PLANNING

KEY WORDS: Drought resistance; **Droughts; Metropolitan areas;** Regional planning; Washington, D.C.; **Water plans; Water resources management; Water shortage;** Water supply; Water supply forecasting

ABSTRACT: The Corps of Engineers' efforts to influence the metropolitan Washington, D.C. area to agree on a regional solution to water supply, while still maintaining service area independence, are examined. The nation's capital and surrounding environs face potentially severe water shortages in the future. The Metropolitan Washington Area (MWA) generally depends on the Potomac River for most of its supply, which is highly variable, subject to both floods and droughts. As population increases in the MWA, the risk of shortages also increase. The MWA's water supply has been studied for years with little or no regional cooperation. The Congress, by its actions, has assumed a lead role for regional water supply planning by acting through the Corps of Engineers, which was directed to make a complete investigation of the water resources needs of the MWA.

REFERENCE: Crews, James E., "Planning for Drought: A Management Perspective," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16078,** March, 1981, pp. 45-59

16093 SMALL-SCALE HYDROPOWER POLICY

KEY WORDS: **Computer models; Energy; Hydroelectric power generation;** Hydroelectric project licensing; Hydroelectric resources; Policies; **Project planning;** Simulation

ABSTRACT: A computer simulation model of the obstacles and incentives to the development of small-scale hydropower in New England is presented. It serves as an effective communication tool between analysts and policymakers, helping them understand the implication of policy recommendations to increase small-scale hydropower development. Only four of the factors affecting development are included in the model: economics, licensing, construction, and retirement. From a financial point of view, the most promising developers are municipalities and investor-owned utilities. In the year 2000, it may be feasible to develop sites costing approximately double the present costs. Small-scale hydropower will generally be developed now only if developers are willing to accept risks. The inflationary effects of licensing and the complexity of the process might be the major disincentives associated with licensing.

REFERENCE: Kirshen, Paul H., and Amlin, Jeffrey S., "Computer Model for Small-Scale Hydropower Policy Analysis," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16093,** March, 1981, pp. 61-76

16086 NAWDEX AND WATER-DATA INFORMATION

KEY WORDS: Data acquisition; Data analysis; **Data collection;** Data links; Information retrieval; **Information systems;** Water collection systems; **Water resources;** Water utilization

ABSTRACT: The National Water Data Exchange (NAWDEX) was established by the United States Geological Survey in 1976. NAWDEX serves as a national focal point for cataloging and indexing water data that are available throughout the nation, and it provides the necessary linkages between the collector and user communities. Available water data have been indexed for over 400 organizations. Additionally, information has been gathered on over 700 organizations that are collectors of water data or involved in water-related programs. Aid in indentifying and locating needed water data is provided by a network of assistance centers located in 45 states and Puerto Rico.

REFERENCE: Edwards, Melvin D., "NAWDEX: Focal Point for Water Data Information," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16086,** March, 1981, pp. 77-83

16080 RESIDENTIAL WATER CONSERVATION

KEY WORDS: Consumer attitudes; Residential density; **Urban planning; Water conservation; Water consumption; Water demand;** Water meters; Water pricing; Water rates; Water reuse; Water salvage

ABSTRACT: Severe pressures on many urban water utilities are the result of water shortages, high treatment costs, scarce supplies and rapid growth. Various water-conservation techniques can be used to reduce the demand for water by urban customers. These include restrictions on use, installation of water-saving devices, metering, horticultural changes, pressure reduction, reuse, and public education. The effects of metering, water-saving devices and price increases on residential water demand are explored for some typical communities. Secondary effects of conservation on revenue production and return flow are also discussed.

REFERENCE: Flack, J. Ernest, "Residential Water Conservation," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16080,** March, 1981, pp. 85-95

16087 COOPERATIVE WEATHER MODIFICATION

KEY WORDS: Cloud seeding; **Clouds (meteorology);** Cooperation; Ice nuclei; **Precipitation (meteorology);** Project management; Radar; **Weather modification**

ABSTRACT: The High Plains Cooperative Program (HIPLEX) is a Federally sponsored research effort in the field of weather modification in the United States high plains states. The Southern Sector of HIPLEX has been conducted in Texas from 1975 through 1979. Funding, management, and project execution are cooperatively shared by Federal, state, university and local entities. Scientific goals of HIPLEX include: establishing a cloud and precipitation climatology; establishing the relationships between large-scale weather conditions and storm cloud populations; relating small-scale weather conditions to cloud development; and examining microphysical and dynamic properties and processes relevant to selected case-study clouds. Technical objectives include: improving estimates of cloud precipitation by radar, evaluating the behavior of cloud systems and developing better observational and measurement techniques.

REFERENCE: Carr, John T., "Cooperative Weather Modification Program," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16087,** March, 1981, pp. 97-104

16077 SOUTHEAST RIVER BASIN WATER RESOURCES

KEY WORDS: Regional analysis; Regional development; Regional planning; **United States;** Water demand; Water plans; **Water policy;** Water quality; **Water resources; Water resources management**

ABSTRACT: The planning and management of water resources in the southeastern United States are surveyed, as documented in the 1975 National Water Assessment. The Second National Water Assessment of 1975 for the South Atlantic-Gulf Water Resources Region points to an overall well-balanced supply-demand ratio for water. Specific areas where severe problems have been identified include: water quantity, fresh-surface; water quantity, ground; and water quality, fresh-surface. How water resources have been affected by past planning policies is evaluated, and how future policy changes may further alter development concepts in the region is described.

REFERENCE: Guess, Clair P., Jr., "Status of Southeast River Basin Water Resources," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16077,** March, 1981, pp. 105-111

16079 CITIZEN GROUPS AND ENVIRONMENTAL GOALS

KEY WORDS: Communication; Community goals; **Community relations; Community support;** Consultants; **Environmental quality;** Organizations; **Public opinion**

ABSTRACT: Citizen organizations can help engineers to set environmental objectives. Public opinion and responses to important issues can be obtained more effectively by working through existing organizations than through presently used public-participation mechanisms. The citizen organization should be treated as a consultant to ensure that the information gathered is properly collected, timely, and reflective of a group's membership. The group should have a work program, specific tasks, and should be paid. The tasks that a group is asked to perform could include writing articles, holding meetings, and establishing suggested environmental objectives.

REFERENCE: Froehlich, David S., "Citizen Groups and Environmental Goals," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16079**, March, 1981, pp. 113-119

16081 DIVERSION FOR WATER QUALITY CONTROL

KEY WORDS: **Diversion;** Flood control; Flow control; Navigation; Reaeration; **Systems engineering;** Water pollution control; **Water quality control; Water resources**

ABSTRACT: Water diverted from the Lake Michigan Watershed to the Mississippi River Watershed includes, among others, water diverted directly into the Chicago River and Canal System. The direct diversions take place at three locations which regulate the flowrates for the purposes of navigation, flood control, and water quality management. An optimization procedure is presented which aids in the management of the system by determining average monthly diversion rates at each of the three control points. The procedure utilizes an efficient network algorithm which determines the minimum diversion necessary to maintain water quality standards in the River and Canal System. Results are reported for existing conditions as well as conditions after 10 instream aeration stations are in operation.

REFERENCE: Male, James W., and Soliman, Karim, "Lake Michigan Diversion for Water Quality Control," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16081**, March, 1981, pp. 121-137

16084 NEW WATER UTILITY PLANNING

KEY WORDS: Coordination; Design standards; Project planning; **Regional planning;** Service needs; **Utilities; Water resources; Water supply**

ABSTRACT: Washington state has two recent laws aimed at facilitating water utilities' predictions of future service and assuring them that they will be able to implement their plans. The Water Resources Act of 1971 provides a system for setting aside sufficient water supply for future domestic needs. Water is reserved by region rather than by system, thereby allowing for a comprehensive look at available resources and mandating intersystem cooperation. The Public Water System Coordination Act of 1977 provides a step-by-step process for water utilities and local government to coordinate utility growth with local development poicies. Key concepts include the indentification of utility service areas and the establishment of regional design standards.

REFERENCE: Rowe, Alan K., and Sander, Daniel K., "New Approaches to Water Utility Planning," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16084**, March, 1981, pp. 139-148

16082 URBAN STORMWATER MANAGEMENT IN SOUTHEAST

KEY WORDS: Erosion control; Flood plain planning; Sediment control; Storm drains; **Storm runoff; Storm water; Urban areas; Water management (applied);** Water pollution

ABSTRACT: The third of a conference series designed to address the most important water resource problems in the Southeast is summarized. Urban stormwater management issues are addressed in the context of: drainage and detention, flood plain management, erosion and sedimentation control, and stormwater pollution control. The strengths and weaknesses of state and local programs are explored, with conclusions and recommendations to correct deficiencies. The Southeast Conference on Urban Stormwater Management, held at North Carolina State University April 10-11, 1979, was directed toward major water resource problems of the following states: Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia.

REFERENCE: Howells, David H., and Grigg, Neil S., "Urban Stormwater Management in Southeast," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16082,** March, 1981, pp. 149-166

16109 SAMPLING TO CHARACTERIZE STREAM PLUMES

KEY WORDS: **Plumes;** Sampling; Sampling designs; **Statistical analysis; Statistical samples;** Stream pollution; Tracers; **Water pollution; Water quality; Water resources**

ABSTRACT: New perspectives are offered on taking samples to determine pollutant concentrations in a stream cross section. By combining plume simulation with a gradient search curve fitting procedure, a means is provided to characterize a pollutant plume by finding its mass flux, center of concentration, and lateral dispersion. Additionally, a number is determined of grab samples needed from the cross section of the plume to find these characteristics. As few as four grab samples from the cross section of a plume are sufficient. If the lateral position of a pollutant in a stream is not known, the negative binomial distribution offers some insight into determining how many grab samples to draw. A consideration of cost factors is included.

REFERENCE: Clarkson, Christopher C., Male, James W., and Adrian, Donald Dean, "Sampling to Characterize Stream Plumes," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16109,** March, 1981, pp. 167-182

16112 GROWTH CONCERNS DEFEAT WATER ISSUE

KEY WORDS: Aqueducts; Conservation; **Cost effectiveness;** Ground water; **Growth projections;** Reclamation; Reservoirs; **Water resources development; Water rights; Water supplies;** Weather modification

ABSTRACT: Santa Barbara County, California, undertook a comprehensive study of local water resources development alternatives. The county then compared these alternatives with the state extending its aqueduct to the county as provided under the state-county contract. The issue of importing from the State Water Project had become both pressing and controversial, with the state pressing for a decision. Importation advocates urged an early enlightened county vote, citing an eventual need and rising costs. Importation opponents claimed importation would prove growth-inducing and, thus, environmentally damaging. An overview is given of the study results and some of the technical and socio-economic considerations that influenced the electorate to reject a $102,000,000 bond proposal that, if successful, would have permitted the importation.

REFERENCE: Lawrance, Charles H., "Growth Concerns Defeat a County Water Issue," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16112,** March, 1981, pp. 183-199

16118 WATER RESOURCES AND RISK AVOIDANCE

KEY WORDS: Hydroelectric power; Irrigation; **Management;** Multiple purpose; **Project planning; Reliability; Risk;** Risk acceptance; **Water plans; Water resources; Water resources**

ABSTRACT: In the past, risk has been considered implicitly in the planning and management of water resources systems analysis. A method is developed through which risk indices are explicitly defined for the operation of a water supply system that provides water mainly to meet regional irrigation and energy requirements. The risk indices obtained can be included in the system objective function to be optimized.

REFERENCE: Nazar, Ata M., Hall, Warren A., and Albertson, Maurice L., "Risk Avoidance Objective in Water Resources," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16118,** March, 1981, pp. 201-209

16123 WRC FLOOD FREQUENCY GUIDELINES

KEY WORDS: Flood estimate; Flood forecasting; **Flood frequency;** Flood hydrology; **Floods; Guidelines;** Hydrology; **Statistical analysis; Water resources management**

ABSTRACT: The Water Resources Council has issued a set of guidelines for determining flood frequency at gaged locations. The need for such guidelines is examined. Application of these guidelines in the Susquehanna River basin has shown the following problem areas: regional skew coefficient map, detection and treatment of outliers, weighting of station and regional estimates, and a lack of specific recommendations regarding the expected probability adjustment. Some possible changes to the guidelines in order to solve these problems are considered.

REFERENCE: Jackson, Donald R., "WRC Standard Flood Frequency Guidelines," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16123,** March, 1981, pp. 211-224

16129 PERSPECTIVES ON WATER CONSERVATION

KEY WORDS: Agricultural watersheds; Energy budget; Municipal water; **Water conservation;** Water law; **Water management (applied); Water resources; Water supply**

ABSTRACT: Water conservation is not an objective in itself, but a part of the broader objective of total water management. The meaning of water conservation has changed during the past 100 yrs from storage of spring runoff to more efficient use of existing supplies. A number of considerations affect the need for conservation and the measures selected to meet this need, including the reasons why conservation is to be adopted, whether conservation is being adopted for emergency or normal conditions, and the means of conservation. Lastly, water and law energy influence conservation adoption and practices. Established water laws may have an important bearing on what can be done and how it is to be done. The need for energy and the cost of energy (especially for pumping and cooling) will be an increasingly important factor in water management in the future.

REFERENCE: Johnson, William K., "Perspectives on Water Conservation," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16129,** March, 1981, pp. 225-238

16131 CONVERSATIONAL WATER DATA RETRIEVAL

KEY WORDS: Computer applications; **Computers;** Computer storage devices; **Data retrieval; Information retrieval;** Information retrieval effectiveness; Information systems; **Water quality**

ABSTRACT: A water quality data management system which simplifies the retrieval of computer-stored data is explained. Everyday conversational language provides the communication between the data retriever and the computer, minimizing the need for specialized training and expertise in computer operations. Information is handled through use of the data base management system SIR (Scientific Information Retrieval) and a FORTRAN program that interfaces SIR with the user. Because all operating commands are built into the system, little or no experience with computers is required.

REFERENCE: Larson, Douglas W., and Bingham, Thomas, "Conversational Water Quality Data Retrieval System," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16131,** March, 1981, pp. 239-243

16136 REDUCING HYDROLOGIC PARAMETER UNCERTAINTY

KEY WORDS: **Frequency analysis; Hydrologic data; Parameters; Probability;** Statistical analysis; **Uncertainty principle;** Water resources

ABSTRACT: A methodology is introduced that can be used in hydrologic frequency analysis to reduce the parameter uncertainty. The methodology consists of developing generalized values of the parameters (mean, standard deviation, and skewness) through the use of a weighting procedure between sample and regionalized statistics. Weights are defined as a function of the variances of the sample parameters and regionalized parameters. The variances of the sample parameters are determined using two nonparametric statistical methods, the jackknife and the bootstrap. The variances of the regionalized parameters are determined through regression analysis. The ability of this methodology is illustrated using flood flow frequency data for the Southwestern United States.

REFERENCE: Tung, Yeou-Koung, and Mays, Larry W., "Reducing Hydrologic Parameter Uncertainty," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16136,** March, 1981, pp. 245-262

16135 RIVER QUALITY AND STORMWATER IMPACTS

KEY WORDS: Combined sewers; Computer programs; Cost effectiveness; Hydrologic models; **Mathematical models; Rivers; Storm runoff;** Storm sewers; **Urban areas; Wastewater treatment; Water pollution control;** Water quality

ABSTRACT: A simplified continuous receiving water quality model has been developed as a planning guide to permit preliminary screening of areawide wastewater management strategies. The model simulates the hypothetical response of the stream or tidal river system to the separate and combined effects of waste inputs from upstream sources, dry-weather urban sources and wet-weather urban sources. The total hours of runoff-producing rainfall throughout a year are separated into storm events. For a given storm event, the runoff and pollutant loads are summarized, and critical dissolved oxygen concentrations are estimated as a function of several hydrodynamic and biochemical parameters. An application to the Des Moines River at Des Moines, Iowa, is presented.

REFERENCE: Medina, Miguel A., Jr., Huber, Wayne C., Heaney, James P., and Field, Richard, "River Quality Model for Urban Stormwater Impacts," *Journal of the Water Resources Planning and Management Division,* ASCE, Vol. 107, No. WR1, **Proc. Paper 16135,** March, 1981, pp. 263-280

U.S. Customary-SI Conversion Factors

In accordance with the October, 1970 action of the ASCE Board of Direction, which stated that all publications of the Society should list all measurements in both U.S. Customary and SI (International System) units, the following list contains conversion factors to enable readers to compute the SI unit values of measurements. A complete guide to the SI system and its use has been published by the American Society for Testing and Materials. Copies of this publication (ASTM E-380) can be purchased from ASCE at a price of $3.00 each; orders must be prepaid.

All authors of *Journal* papers are being asked to prepare their papers in this dual-unit format. To provide preliminary assistance to authors, the following list of conversion factors and guides are recommended by the ASCE Committee on Metrication.

To convert	To	Multiply by
inches (in.)	millimeters (mm)	25.4
feet (ft)	meters (m)	0.305
yards (yd)	meters (m)	0.914
miles (miles)	kilometers (km)	1.61
square inches (sq in.)	square millimeters (mm^2)	645
square feet (sq ft)	square meters (m^2)	0.093
square yards (sq yd)	square meters (m^2)	0.836
square miles (sq miles)	square kilometers (km^2)	2.59
acres (acre)	hectares (ha)	0.405
cubic inches (cu in.)	cubic millimeters (mm^3)	16,400
cubic feet (cu ft)	cubic meters (m^3)	0.028
cubic yards (cu yd)	cubic meters (m^3)	0.765
pounds (lb) mass	kilograms (kg)	0.453
tons (ton) mass	kilograms (kg)	907
pound force (lbf)	newtons (N)	4.45
kilogram force (kgf)	newtons (N)	9.81
pounds per square foot (psf)	pascals (Pa)	47.9
pounds per square inch (psi)	kilopascals (kPa)	6.89
U.S. gallons (gal)	liters (L)	3.79
acre-feet (acre-ft)	cubic meters (m^3)	1,233

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URBANIZATION AND WATER SUPPLIES FOR NORTHEASTERN COLORADO[a]

By Robert R. Smith[1]

INTRODUCTION

Following World War II, areas such as Los Angeles, the San Francisco Bay area, and the Pacific Northwest began feeling growth pains. In more recent years the Eastern Front-Range of the Colorado Rocky Mountains has incurred similar growth characteristics. For example, during the period 1970 through 1977, cities such as New York, Philadelphia, and Boston saw their populations decrease at rates of 8% to 10%; Denver, Colorado, during the same period, incurred a population increase of over 20%. This was further reflected in Northeastern Colorado where, during the same period, population increased from approximately 260,000 to over 380,000, or 46%.

The impacts of this rapid urbanization on the water resources available to the Northeastern Colorado area and on its water distribution systems are numerous. The options available to resolve the problems associated therewith are somewhat limited. To better understand these impacts, however, one must first have a basic understanding of the area and its base water supplies.

Northeastern Colorado has been agriculturally oriented in terms of its basic economy since about 1850, when the development of over 850,000 acres (344,250 ha) of prime farm land began. In an area that receives less than 14 in. (355 mm) of rainfall annually, this industry, obviously, must depend on irrigation practices to survive. Thus, the period between the mid-1880s and early 1900s saw a great flurry of reservoir and canal construction along the tributaries of

[a]Presented at the April 14–18, 1980, ASCE Convention and Exposition, held at Portland, Oreg.

[1]Dist. Engr., Monterey County Flood Control and Water Conservation Dist., P.O. Box 930, County Courthouse, Salinas, Calif. 93902.

Note.—Discussion open until August 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on April 18, 1980. This paper is part of the Journal of the Water Resources Planning and Management Division, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. WR1, March, 1981. ISSN 0145-0743/81/0001-0001/$01.00.

the South Platte River Basin to capture spring runoff and retain it for beneficial use during the summer growing season. In later years over 4,500 wells were also constructed throughout the basin to help augment surface supplies. Early on and especially following the drought of the early 1930s, it was quite clear, however, that the land under irrigation at the time on the average would be water short without the development of some source of new water for the area.

Water users in Northeastern Colorado had looked enviously for many years to the surplus flows of the Upper Colorado River on the Western Slope of the Continental Divide as a potential source of supply for this new water. If only it could be developed and transported to the South Platte Basin!

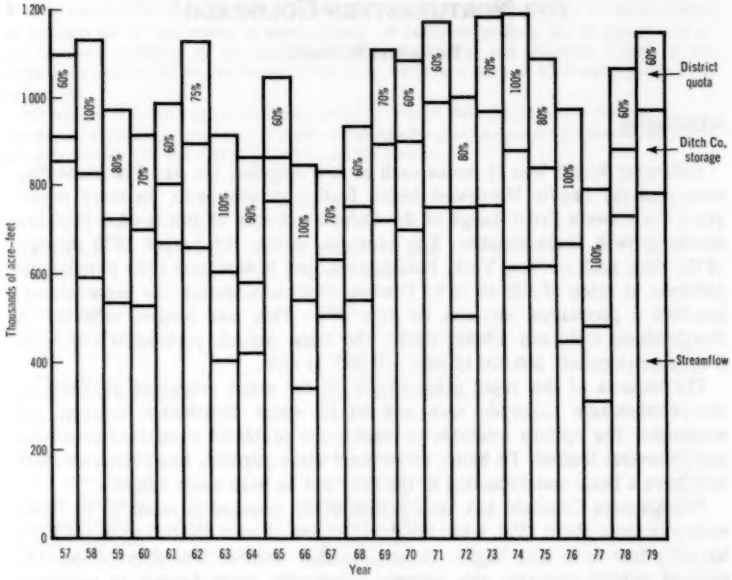

FIG. 1.—Available Water Supply—Tributary Service Area

By a vote of the people in 1937, the Northern Colorado Water Conservancy District was formed to represent the water users of Northeastern Colorado in contracting with the United States Department of Interior, Bureau of Reclamation, for the construction of the Colorado-Big Thompson Project (CBT), a transbasin diversion project which would collect surplus water from the Upper Colorado River and by a series of dams, conduits, power and pumping plants, export this water from that Basin to the Big Thompson River, a tributary of the South Platte Basin on the Eastern Slope. Construction of this Project got under way in 1938 and was completed in 1956. The Project was designed and constructed to export an average of 310,000 acre-ft (382,200,000 m^3) annually.

This water was then to be used as a supplemental supply to the base flow of the four major tributaries of the South Platte Basin—the Poudre River, Big Thompson River, St. Vrain River, and Boulder Creek.

Since 1957, the first full year of Project operation, the Project has yielded approximately 217,000 acre-ft (267,600,000 m^3) of supplemental transbasin water annually, ranging from a minimum of about 123,000 acre-ft (151,700,000 m^3) to a maximum of over 309,000 acre-ft (381,000,000 m^3) (Fig. 1). With in-basin surface supplies averaging about 597,000 acre-ft (736,000,000 m^3) from these major tributaries, this represents an average annual supplement to the basin of approximately 36%.

In 1957, the population of the District service area was approximately 135,000. The current population of this same area is in excess of 419,000 (Fig. 2). In 1957 the annual domestic water demand was approximately 29,000 acre-ft (35,800,000 m^3). The current demand for domestic water totals over 95,000

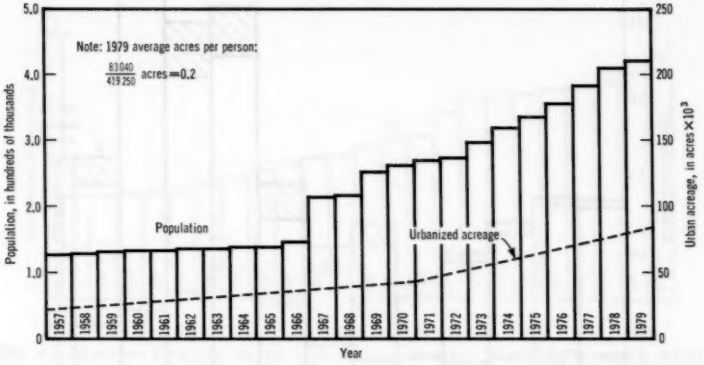

FIG. 2.—Northern Colorado Water Conservancy District: Population Versus Urbanized Acreage

acre-ft (117,100,000 m^3) (Fig. 3). In other words, over the past 22 years annual demand for domestic water has increased by approximately 66,000 acre-ft (81,400,000 m^3), or 228%, resulting from a growth increase of over 210% during the same period, 90% of which has occurred since 1966.

Water Supply Impacts

Since the South Platte River Basin tributaries have been overappropriated for years in terms of providing any new undeveloped water for domestic beneficial use, the source of supply to support this growth has been acquired gradually by the cities, small towns, rural domestic water associations, and industrial users of the area through the purchase of surface water rights previously used for irrigation. In addition, supplemental Colorado River water diverted by the CBT Project primarily for agriculture users continues to be purchased from the irrigator for these uses. This can be further illustrated by looking at the

change in District Allotment Contracts for the municipal-domestic class of service from 1957 through 1979 (Fig. 4). In 1957, for example, only 16% of the total CBT Project supply was allotted for this purpose. In contrast, 35% of the total available project supply is currently allotted for use under this class. All of this suggests, of course, that land previously under irrigation is gradually being converted to urbanization or dry-land farming.

Recent analysis of land conversion within the boundaries of the District suggests that some 40,000 acres to 60,000 acres (16,200 ha to 24,300 ha) of mostly irrigated farm land has been converted to support urbanization since 1957, with most of this conversion occurring in the past decade or so (Fig. 2).

Since water rights in Colorado are property rights, the value of which is

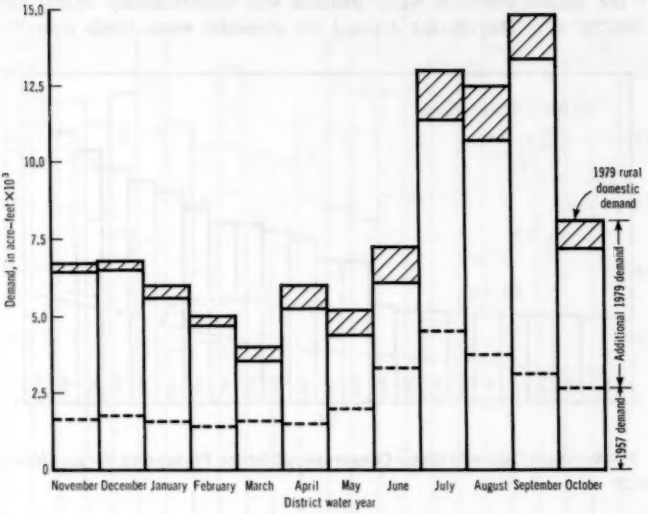

FIG. 3.—Municipal-Domestic Water Demands Within Northern Colorado Water Conservancy District

established by the rules of supply and demand, the impact of urbanization can also be illustrated by the rapid escalation in the average unit purchase price paid for CBT Project water by various users since 1957 (Fig. 5). This tremendous escalation in pricing can, to a large degree, be attributed to the high demand for domestic and industrial water supplies and the ability of those users within the area to offer a maximum dollar value for it. The economics of the situation are usually quite attractive to many farmers who in recent years have seen little change in the net return on their productivity. It has been a regular occurrence, therefore, to acquire irrigation water rights for domestic and industrial purposes as a result of a negotiated agreement between the parties, as opposed to condemnation through eminent domain on the part of the municipalities.

Obviously growth cannot occur at the rate seen in the area without the need to develop additional water supplies for expanding public utilities and new area industries. Since approximately 1970, Public Service Company of Colorado, for example, has put on line one nuclear plant and is nearing completion on another coal-fired steam plant within the boundaries of the District. In addition, Platte River Power Authority, the electrical utility arm of four major cities in the District, has begun construction of a coal-fired steam plant in the area. Total installed capacity of these plants will be approximately 1,080 MW with a maximum expandable capacity to approximately 3,580 MW. The water supply requirements for these new plants will range from approximately 16,000 acre-ft to 47,400 acre-ft (19,700,000 m^3 to 58,400,000 m^3) at maximum installed capacity. Of importance here is the fact that these water requirements are 100% consumptive in use. In addition, industries such as Kodak of Colorado, IBM, Hewlett-Packard, Water Pik, and Woodward Governor continue to expand their operations in this area, and consequently their need for industrial and domestic water continues.

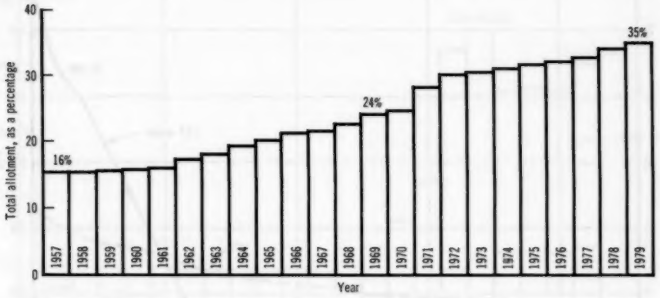

FIG. 4.—Northern Colorado Water Conservancy District: Municipal-Domestic Allotments Contracts

The growth in Northeastern Colorado as projected will probably continue to occur along the Eastern Front-Range of the Rocky Mountains upstream of most primary irrigated lands. This, coupled with the fact that the area's consumptive use for domestic purposes is less than that for irrigated agriculture, could theoretically provide levels of return flow available for use on irrigated lands downstream to the degree that a projected population of approximately 1,000,000 could conceivably still support up to 700,000 acres (283,000 ha) of irrigated farm land with no significant change in present basin water supplies. This would depend to a large extent on the ability to reuse existing water supplies without injury to downstream uses.

New Water Supply Alternatives

Obviously, a solution to some of these impacts—short of some unknown type of rigid growth control—is another water supply for the sole purpose of supporting reasonable planned growth. This would help keep intact over

850,000 irrigated acres (344,250 ha) of prime farm land currently supporting an annual agricultural industry of over $250,000,000.00 (Fig. 6). The question would seem to be: Where can new undeveloped water be found? Some of the options considered in Colorado and other western states revolve around urban and on-farm conservation practices, such as metering, lawn watering restrictions, irrigation management scheduling, development of additional ground-water supplies, and weather modification programs which address both winter and summer cloud seeding. All of these options are to some degree currently in practice within the state and within the District service area. However, a fourth option, and one near to becoming a reality, is the diversion of additional undeveloped Colorado River water from the Colorado Basin, through new diversion facilities and utilization of unused capacity in the existing Colorado-Big Thompson Project facilities. A new project, known as the Windy Gap Project,

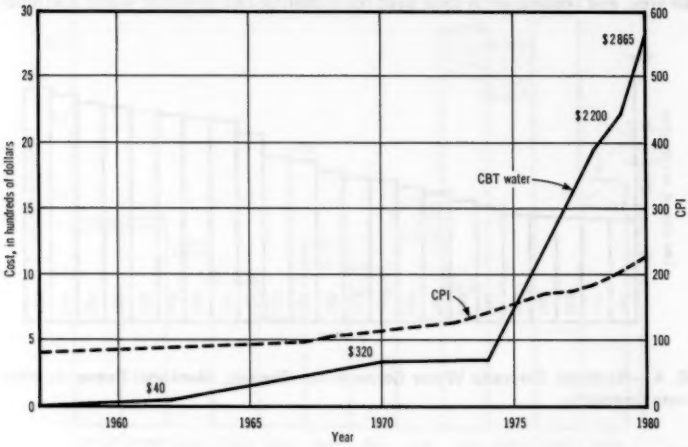

FIG. 5.—Cost of CBT Project Water Versus Consumer Price Index (CPI)

will develop approximately 50,000 acre-ft (61,700,000 m^3) of new water annually from the Colorado River Basin at a capital cost of approximately $700.00 per acre-ft. This is considerably less expensive than the purchase of agricultural water currently selling for approximately $3,000.00 per acre-ft, as indicated on Fig. 5.

Currently, under Colorado's entitlement to flows of the Colorado River under the Colorado River Compact, there is approximately 1,000,000 acre-ft (1,200,000,000 m^3) of undeveloped water available for beneficial use in the state (Fig. 7). The water developed by the Windy Gap Project would be a portion of this previously undeveloped supply. The project is being financed by five major cities and one electrical utility within the boundaries of the District. Sale of revenue bonds administered by a Municipal Subdistrict of the District will finance the project cost of approximately $35,000,000.00. The current estimated

annual cost of this water will be approximately $141.00 per acre-ft, including debt service retirement, carriage costs associated with use of the CBT project facilities, operation, maintenance, and electrical pumping costs (Table 1). The current annual cost associated with amortization and annual assessments for Colorado-Big Thompson Project water, at $3,000.00 per acre-ft, is approximately $217.00.

Another aspect of developing this new water supply is the fact that it will be foreign water to the South Platte Basin, and thus under Colorado law will be subject to 100% consumptive reuse. Even negating the reuse aspect of this water, an additional population of over 200,000 could be served with return flows therefrom being available to irrigate 30,000 to 40,000 additional acres (12,150 ha to 16,200 ha). Considering a 50% reuse, the water requirements for an additional population of approximately 250,000 could be met with return flows available to support irrigated agriculture on an additional 10,000 acres (4,050 ha) of land.

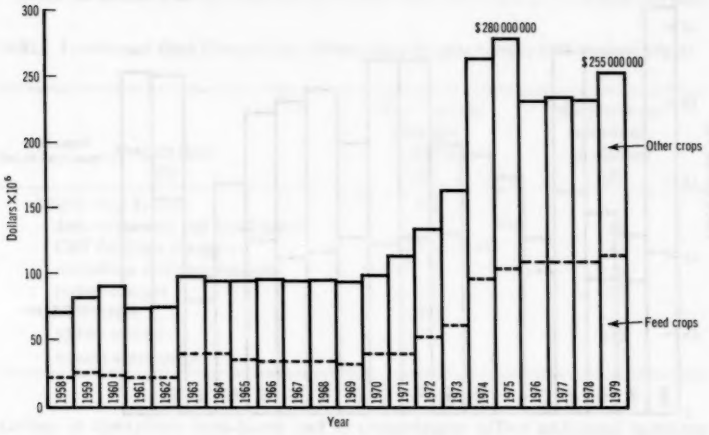

FIG. 6.—Northern Colorado Water Conservancy District Crop Valuation

In addition, this new water supply will generate approximately 90,000,000 kWh of new electrical energy annually through the 184-MW CBT power system for use in Northeastern Colorado.

Water Distribution System Impacts

The second area of impact associated with urbanization occurs within the water distribution system itself. The CBT Project water distribution system operated and maintained by the District will be used as an example. The effects on the system should be similar to those on any other system in the area that provides a raw water supply to irrigated agriculture as well as for municipal-domestic uses.

The water distribution system of the Project consists of three major reservoirs ranging in capacity from 13,000 acre-ft to 153,000 acre-ft (16,000,000 m^3 to 188,600,000 m^3). In addition, over 80 miles (128 km) of open canal, tunnels, and inverted siphons provide delivery capacities ranging from 8 cfs to 1,500 cfs (0.2 m^3/s to 42.0 m^3/s).

The demand curve for domestic water from the system takes on quite a different shape in 1977 and 1979 as compared to 1957, both in time and quantity (Fig. 8). A peak monthly demand for municipal-domestic water service of over 10,000 acre-ft (12,300,000 m^3) (110 mgd) is not now uncommon. In addition, a minimum monthly demand of nearly 1,000 acre-ft (1,200,000 m^3) (11 mgd) is now being met from the system throughout the water year.

Within the system as now constructed is the ability to provide domestic raw

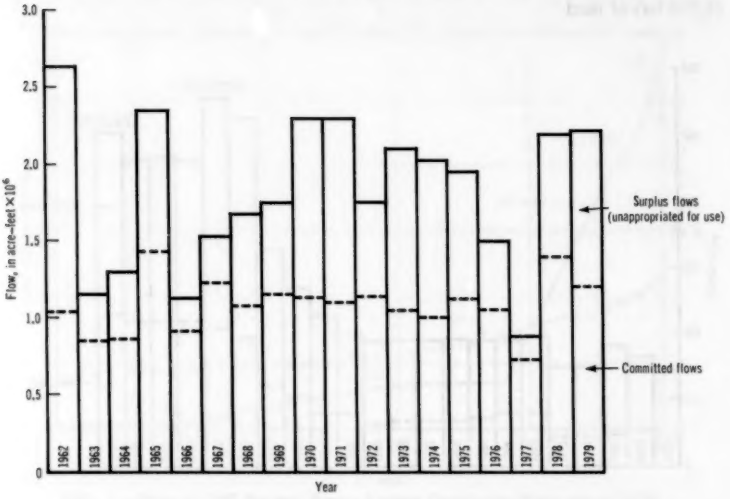

FIG. 7.—Colorado River Flows at Dotsero, Colorado

water service to some 37 cities, towns, and rural domestic water treatment facilities either by direct delivery or by exchange through other systems.

Since 1957, the system has seen some 15 water delivery facilities added to it, including two major expansions to the outlet works of one of the reservoirs to provide improved water delivery service to some 21 domestic entities. Most of these facility additions are in the form of new canal turnouts or closed conduit taps to the reservoir outlet and power penstock works. Most project improvements were constructed to provide year-round water service to the customer, as opposed to the open canal and turnout system associated with irrigation deliveries during the summer months only.

Canal system maintenance in the form of lining replacement, dragline cleaning, flume protection, and joint sealing were for years activities that could be

accomplished between late October and early May when the system was down. The change in demand curve, as reviewed earlier, has in some years forced these activities into a much smaller time frame for completion, and to some degree has been responsible for an increase in District operations and maintenance staffing in recent years.

Canal system water quality, in terms of chemicals used to control algae within the system, is now becoming a concern of some domestic water users taking delivery of their raw water supplies below the points of treatment. Since the late 1950s, the District has controlled algae by injecting copper sulfate into the canal systems. In recent years, most domestic water users on the system have requested that their delivery facilities be shut down when this maintenance procedure is being performed. Since the use of copper sulfate for algae control is a weekly occurrence between late May and early September, it has resulted in additional operations time required on the part of the operator in conjunction with the requested interruption of service.

Some canal automation facilities have been added in recent years which provide

TABLE 1.—Annual Cost Comparison, Windy Gap Project Versus CBT Project Water

Project item (1)	Total cost per acre-foot, in dollars (2)	Item cost per acre-foot, in dollars (3)
Windy Gap Project	141	
debt retirement and fixed costs		80
CBT facilities charge		13
operations and maintenance		6
power charges		42
CBT Project	217	
$3,000 × 0.07		210
annual assessment		7

savings in operations man-hours and to some degree offset additional operator time now incurred in these added activities. Furthermore, many of the new domestic systems are metered and require only weekly or monthly inspection by the operator.

The use of soil sterilants and herbicides along the canal system right-of-way (for the control of broadleaf weeds), and access road growth over the years, have also changed to some degree because of their threat to an ever increasing potable water supply and adjacent land development. The labeling and restricted use of certain sterilants and herbicides as a result of the Federal Pesticide Act have forced the District and other water supply entities to utilize products that are either more expensive or less effective, or both, to control weeds within the canal right-of-way system.

One of the greatest impacts on the system attributable to urbanization is that of urban development adjacent to the canal system itself. In the past decade, numerous subdivisions have been developed along canal rights-of-way, requiring major changes in right-of-way fencing requirements and policies, new public

road crossings, utility crossings, and, as previously mentioned, a severe reduction in the application of herbicides for weed control. The tremendous increase in trespass to the system as a direct result of this change in land use has also necessitated the development of a system-wide safety sign program, and the addition of numerous access road gate structures and precast concrete buildings to minimize vandalism to facilities and any District liability associated therewith. All of these items have in one way or another increased the cost of operating

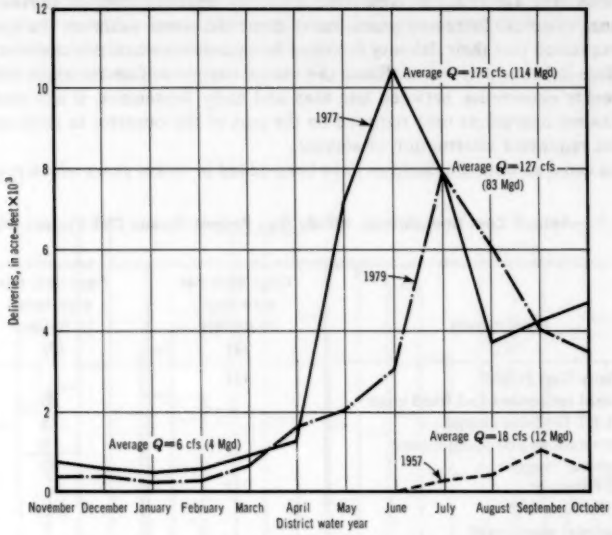

FIG. 8.—CBT Project Deliveries to Municipal-Domestic Uses

and maintaining the system in terms of increased time required to perform typical duties.

Conclusions

Urbanization versus agriculture has always implied conflict or competition. In a broad sense this has not been and need not be true. Cooperation between these areas of interest can provide for all foreseeable needs for both. So far the expanding needs of minicipalities and industry for water and land have been met for the most part by the purchase of agricultural water rights with some reduction in irrigated acreages. Municipal-domestic uses must have a priority over other uses, and the Colorado Statutes provide for this. This category of use can also afford to pay more than the farmer for the water supply through the free market system as prices continue to rise. Municipal and industrial users can thus afford to develop and appropriate what little water is left as

flood flows in the South Platte Basin or develop "new water" from other basins.

The Windy Gap Project represents this type of "new water" development. Although it is currently going through all the typical environmental hurdles encountered by water resource projects today (resulting in project construction costs in the neighborhood of two times its original estimate in the early 1970s), it is still an attractive project in terms of current benefit/cost. When constructed, and coupled with proper management of all basin water supplies, it should assure Northeastern Colorado of a stable water supply to support reasonable planned growth and the protection needed to the primary base economy of the area—irrigated agriculture.

Obviously, urbanization impacts on a water distribution system, although numerous, are for the most part offset by an increase in labor force requirements and the costs associated therewith are ultimately passed on to the consumer through the water rate structure.

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CHANGING OBJECTIVES: CHICAGO METRO FLOODWATER PLAN[a]

By Frank L. Kudrna,[1] M. ASCE and Roger K. Olson[2]

INTRODUCTION

Within the Chicago metropolitan area there was an urgent need to formulate plans for management of floodwater and related resources which would be acceptable to the public and agencies, and at the same time satisfy requirements for federal implementation funding.

In order to accomplish this complex task in the Chicago metropolitan area, watershed steering committees with close citizen, community, and agency involvement at a grass-roots level were formed. Technical planning assistance was provided by the United States Department of Agriculture (USDA), Soil Conservation Service, and local sponsors. Broad interests of steering committee representatives encouraged formulation of plans containing a unique balance of structural and nonstructural elements which merged into a comprehensive plan with broad-based support. Structural measures range from excavated reservoir, dike, and channel improvement, to modification of existing structures. Nonstructural elements include flood-plain regulations, channel operation and maintenance, sediment and erosion control ordinances, and treatment of critical

[a]Presented at the October 16–20, 1978, ASCE Annual Convention and Exposition, held at Chicago, Ill.

[1]Dir., Illinois Dept. of Transportation, Div. of Water Resources, Marina City Office Building, Room 1010, 300 North State, Chicago, Ill. 60610.

[2]Staff Leader, Resource Coordination Staff, Metropolitan Sanitary Dist. of Greater Chicago and Soil Conservation Service, United States Dept. of Agr., P.O. Box 475, Lisle, Ill. 60532.

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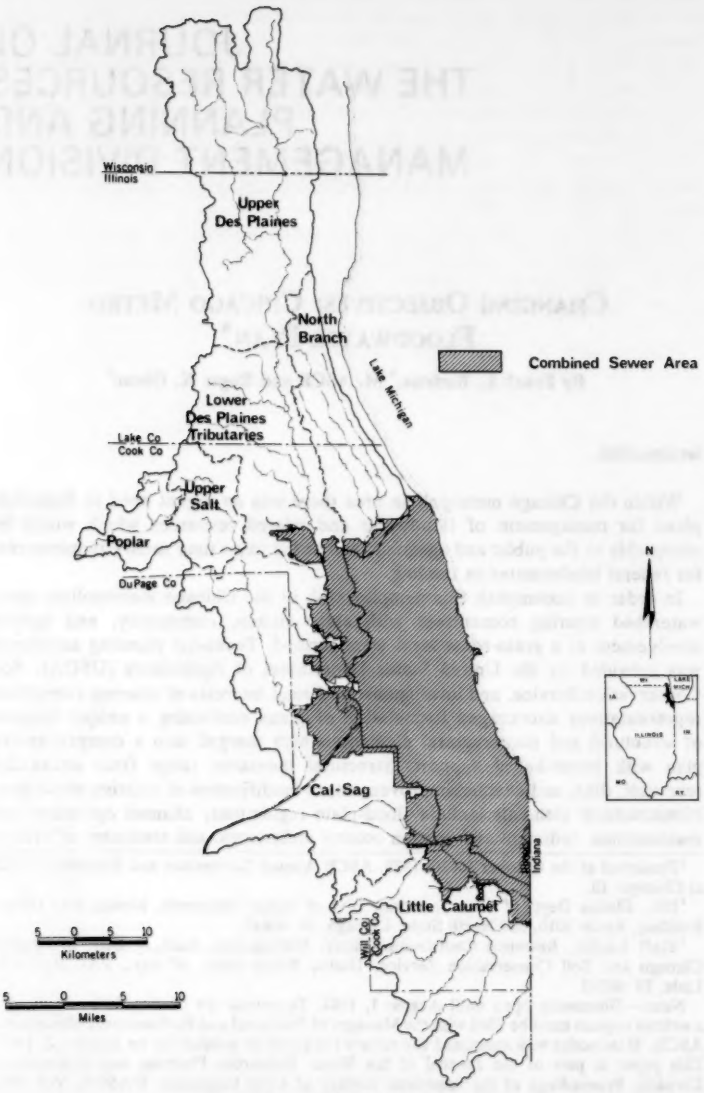

FIG. 1.—Chicago Metro Area River Basin

sediment production areas and wetland acquisition. This plan was published in six separate floodwater management plans and is summarized in "Our Community and Flooding: A Summary of Floodwater Management Plans for the Chicago Metropolitan Area" (6) published in June, 1976, culminating the 5-yr study of the 1,260 sq mile (3,263 km^2) planning area.

The purpose of this paper is to describe the flooding and related resource problems, the steering committee function, and the planning process. A case example from steering committee formation through early plan implementation will be highlighted. The overall process is now being used as a model in other watershed areas.

Problems

Floodwater management and related water resource problems in the Chicago metropolitan area are related to a number of physical as well as cultural factors. The basic physical factor affecting flooding is the geology of the region. The study area is located in a band of glacial morainal topography with only slight relief paralleling the southwest shore of Lake Michigan. Well-developed, stream-cut valleys are essentially absent. The natural drainage pattern is poorly developed with streams occupying broad swales between the moraines. Undrained depressions in the form of wetlands are common.

Glacial Lake Chicago, which stood 60 ft higher than present Lake Michigan, left a relatively flat lake plain. As a result of this relatively flat topography, flood plains vary greatly in width, and floodwater may cross watershed divides.

A major influence on flooding problems and their ultimate solution is the type and distribution of existing sewer systems (Fig. 1). A 375.3 sq mile (972 km^2) area of the City of Chicago and many of the adjacent older suburban communities are served by combined sanitary and storm sewers feeding sewage treatment plants. During periods of heavy rainfall, runoff exceeds the delivery capacity resulting in sewage backup and direct bypass to rivers and streams. In addition, treatment plants, unable to treat the combined sanitary-stormwater peak flow, are forced to bypass untreated effluent into receiving streams. Alternative solutions to this problem involved replacement and separation of thousands of miles of existing sewers. With clean water recognized as a national goal and mandated by federal legislation, the Metropolitan Sanitary District of Greater Chicago (MSDGC) adopted TARP (2), the Tunnel and Reservoir Plan (Fig. 2). This plan provides for collection of combined runoff through drop shafts and delivery to mined storage areas through rock tunnels. Approximately 126,000 acre-ft of storage will be provided, and the rock tunnel delivery system, with diameters up to 36 ft, will be 125 miles long. During post storm periods, the stored combined runoff will be pumped to treatment plants. Total cost of federally funded construction will be over 1.5 billion dollars.

In the separate and unsewered areas, the flood damage problems have been thoroughly surveyed through the Chicago Metropolitan Area River Basin Study. Current damage in the River Basin Area is estimated to be over $6,000,000 annually. The six watersheds (Fig. 1) have a total of approximately 100,000 acres (40,500 ha) of flood plain (100-yr frequency) encompassing all or parts of 200 communities. Of the 7,500,000 population, 330,600 (4.4%) live in flood plains, and this proportion is expected to increase to 5.3% (513,600) of the

9,760,000 population projected for the year 2000. Total average annual damage is projected to increase to $12,000,000 by 2000 as a result of increasing affluence.

Several types of flood damage occur. Flooding damages some 13,200 residential buildings and 520 commercial and manufacturing buildings. Also subjected to flooding are 10 major transportation arteries and 25 secondary traffic routes. Major economic losses are incurred from this highway flooding, as traffic is

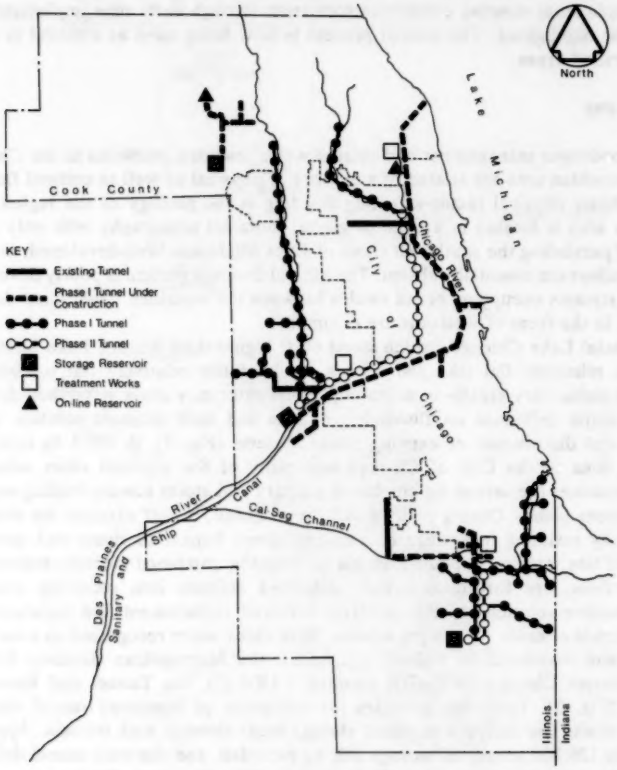

FIG. 2.—Tunnel and Reservoir Plan

disrupted, and access to homes and commercial buildings is interrupted. Flooding also aggravates problems of channel maintenance and necessitates debris removal after storm events.

A major socioeconomic problem occurs as frequent residential flooding causes neighborhood degradation through reduced quality of living space and reduced structural life. This process lessens the confidence of individuals and financial institutions in the neighborhood, and this in turn produces further declines.

Commonly this results in postponement of needed repairs and frequent sale of homes to transfer the problem to an unsuspecting owner.

Several factors, in addition to the geographical and geological factors previously considered, influence flooding. Principal among those is the rapid post war population growth and suburban expansion which peaked in the 1950s. Growth pressures of that period resulted in development of many flood-plain areas. At that time urbanization of those areas was considered to be politically sound and economically expedient. Orderly development was the rule of the day, and areas adjacent to service facilities were given priority for development with little regard to natural hazards such as flooding.

Poor management of natural resources has also contributed to increased frequency and magnitude of flooding, e.g., erosion from agricultural land and areas undergoing development produce sediment which obstructs drainage facilities and reduces channel capacities. This sediment also adversely affects water quality. In addition, as areas have been developed, wetlands acting as natural storage areas have been filled, infiltration has been reduced in proportion to paved and roofed areas, and storm sewers rapidly delivered the increased runoff to flood plains. The common development attitude has been that on-site considerations are far more important than the cumulative adverse off-site effects.

Another major contributor to increased flooding has been the practice of flood-plain filling. With a flood hazard recognized, developers have filled property above supposed record flood elevations. The result has been increased flood stages resulting from lost storage and conveyance capacity. As a final result, additional properties are added to the flood plains, and the problem is both expanded and partially transferred.

Alterations to stream channels, either directly by man or indirectly through man's mismanagement of natural resources, have contributed to the flooding problem. Of obvious importance is channel enlargement which has been particularly common in the Chicago area where natural channels are poorly developed. While these channels may provide flood protection to adjacent areas, the downstream effects have been commonly detrimental. Inadequate bridge openings have also produced adverse effects. Contributions to flood damages have also occurred due to sedimentation and growth of riparian vegetation, both of which reduce channel capacity.

Government, in the past, within the region has been largely ineffectual in dealing with floodwater management problems for several reasons. Of primary importance is the fact that the problems have been approached within the confines of single, small political units, generally municipalities. The regional or cross-community problems have thus been ignored, and solutions were sought on the basis of political expediency. No single agency had been able to deal with these problems from the standpoint of an overall floodwater management point of view. In fact, agency responsibilities were poorly defined, unclear, and conflicting. Communities were seldom able to cooperate to solve mutual floodwater problems; in many cases, one community's solution adversely affected downstream areas. Planning at various governmental levels seldom adequately recognized natural hazards such as flooding and soil limitations.

The Chicago Metropolitan Area River Basin Study was organized to solve floodwater and related water resource management problems. Its organization was stimulated by the success of the planning effort for the PL-566 Upper

Salt Creek Watershed Project (4) in suburban Cook County. Development of this plan proved to the local people, the MSDGC, and the Soil Conservation Service (SCS) that floodwater management plans can be developed for complex urban areas. In 1971, the MSDGC and the SCS entered into a cooperative agreement under the authority of Section 6 of Public Law 566. The $2,800,000

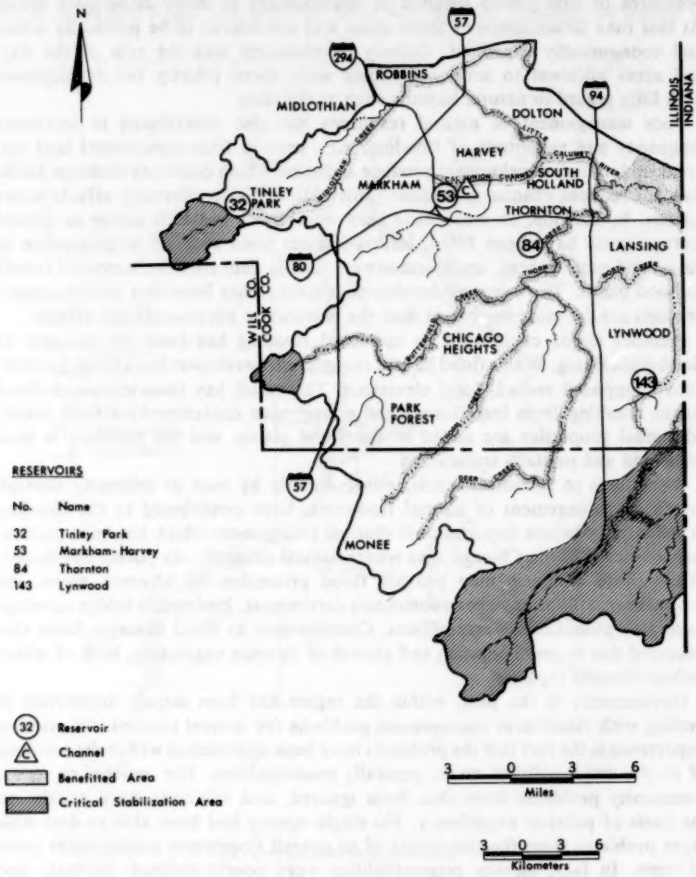

FIG. 3.—Little Calumet River Watershed Plan

cost of the 5-yr effort would be shared between MSDGC and SCS. The metropolitan area outside of the Upper Salt Creek Watershed was divided into five watersheds: Des Plains River, Little Calumet River, North Branch Chicago River, Poplar Creek, and Calumet-Sag Channel. Each would be planned to the same intensity as the Upper Creek Project.

Steering Committees

Public involvement has been the key to success for the River Basin Study. Citizen steering committees were formed in each of the five watersheds. These local committees have representation from a broad range of both public and private interests.

Interested citizens form the core of the committees. Many of these people experience flood damage to their homes. Others recognize flood impacts on their communities and are thus motivated to participate. The experience and observation of long-term residents forms an important historical perspective of flooding problems which may be unrecognized by newer residents. Local citizens also bring continuity to the steering committees in contrast to local officials whose tenure may be brief. The local citizen's role is further strengthened by his objectivity, being relatively free from political influence.

Steering committee representation also comes from environmental groups, municipal and other local government, neighborhood organizations, regional agencies, special districts, and planning commissions. Each of these has a role in floodwater management. Although these entities are at times in conflict, the steering committees provide a forum for communication resulting in mutual support of common goals. Noteworthy among the representatives are forest preserve districts, which have broad authority in Illinois, drainage districts, soil and water conservation districts, park districts, and planning commissions.

Communication between the steering committees is effected through the Chicago Metropolitan Area Council of Steering Committees which is composed of the chairman of each of the individual committees. The council furthers communication in floodwater management by sponsoring each year an interagency advisory meeting. Participating in this meeting are representatives of the steering committees, governmental units, agencies, and elected officials.

Decision making and leadership for plan development are the functions of the steering committees. The plans ultimately developed reflect the alternatives chosen by the committees to satisfy their water resource management objectives. Decisions concerning plan elements are made in public meetings. The plans thus become instruments of the concerned populace with broad public support, not plans imposed from above by a select group not fully aware of public needs.

Case Study—Little Calumet River Watershed Plan

The Little Calumet River Watershed covers 136,500 acres in southern Cook and northeastern Will Counties, Illinois (Fig. 3) (7).

Technical assistance in preparation of the plan was furnished by the United States Department of Agriculture, Soil Conservation Service and Forest Service, the Metropolitan Sanitary District of Greater Chicago, and the State of Illinois (7).

Floodwater damage is a major watershed problem and is increasing due to urbanization and flood-plain encroachment. Flooding causes extensive damage to approximately 6,866 homes, personal property, and 142 businesses. In addition, flooding closes roads isolating many areas and interrupting transportation on major highways. Approximately 10,800 acres are subject to inundation by a

projected condition 100-yr frequency flood. Future floodwater damages to existing development will average $3,223,900 annually. Future development in identified flood plains is now regulated by the State of Illinois (7).

Erosion on lands being converted from agricultural, forest, and idle land uses to urban uses produces sediment which adversely affects surface water quality, increases sewage treatment costs, clogs storm sewers, and is deposited in downstream channels. Erosion on 30,000 acres of agricultural land reduces long-term productivity and also produces similar sedimentation and water quality problems (7).

Recreation and open space needs in the watershed currently exceed available resources. These needs will grow as population increases and development proceeds (7).

TABLE 1.—Little Calumet River Watershed Plan: Data Summary

Physical (1)	Financial (2)
Number of reservoirs—4	Installation costs ($1,000):
Miles of channel modification—20	Construction—26,791.3
	Engineering—2,028.3
Storage capacity, in acre-feet:	Land rights—8,061.0
Sediment—624	Project admin.—2,241.9
Floodwater—11,700	Total—40,401.8
Recreation—85	
Total—12,409	Cost sharing:
	Federal—73.4%
Surface area, in acres:	State & Local—26.6%
Sediment—78.6	
Recreation—12.7	Maintenance costs (average annual):
Floodwater—150.6	Structural measures—102.4
	Recreation facilities—37.0
Recreation development	Flood proofing—3.9
Flood proofing	Total—143.3
Channel maintenance	
Land treatment measures*	

*Benefits and costs are not shown.

The Watershed Plan (see Table 1) has been developed to: (1) Provide watershed protection and environmental enhancement through an accelerated land treatment program; (2) reduce flood damages by implementing floodwater retarding structures, channel work, stream channel maintenance, and flood proofing; and (3) provide increased water-based recreation (7).

The accelerated land treatment program provides $2,729,000 for watershed protection and critical area stabilization on 21,650 acres. This includes $795,500 for the preparation of resource conservation plans and technical assistance in installing required measures (7).

Nonstructural measures consist of a channel maintenance program and a flood-proofing program. The cost of these programs, estimated at $572,600 for channel maintenance and $186,000 for flood proofing will be borne by local agencies. Additional costs will be incurred for administration (7).

Planned structural measures consist of three single purpose excavated floodwater retarding structures, one multiple-purpose structure (floodwater storage plus recreational storage and associated facilities), and channel work on 1.99 miles of previously modified stream. Installation cost of the structural measures is estimated to be $37,401,300 exclusive of project administration. The PL-566 portion of this cost is $28,819,600, while the other than PL-566 or local cost is $8,581,700 (7).

Total estimated project administration costs are $2,241,900. The PL-566 funds will provide $1,681,400 and local funds will provide the remaining $560,500 (7).

Implementation of this plan will reduce average annual floodwater damages by 98% providing $3,157,700 in annual benefits. Recreational facilities to be installed will provide 123,400 recreation visits annually valued at $185,100. The land treatment program will reduce average annual erosion on agricultural land from 8.4 tons/acre to 3.8 tons/acre. Sediment leaving urbanizing land will be reduced from 11 tons/acre to 2 tons/acre annually. Sediment pollution of waterways and stream channel maintenance costs will be reduced (7).

Project installation is scheduled to be completed in a 10-yr period. Local sponsoring organizations will, upon completion of each structural measure, assume full operation and maintenance responsibility as provided by specific operation and maintenance agreement (7).

Total average annual benefits of the plan are $3,342,800. Total average annual costs are $2,882,600. The resultant benefit-cost ratio is 1.2:1.

Developing the Little Calumet Watershed Plan required approximately 5 yr. Water Resource Council Principles and Standards for Planning Water and Related Land Resources (8) were used as directed by USDA procedures (5). Early studies to determine component needs included preparation of an Environmental Resource Inventory containing detailed information on water quality, land use, stream and flood-plain biota, natural areas, water bodies, wetlands, unique geologic sites, open space, and projections of the future condition of these elements. Additional studies included hydraulic and hydrologic analyses to determine flood profiles, and detailed mapping (1 in. = 400 ft, contour interval = 2 ft) of 109 miles of flood plains. Detailed surveys, including elevations of critical water entry and beginning damage points were then determined for some 7,000 flood-plain buildings. Depth-damage curves for each of the major types of buildings were developed on the basis of interviews, published data, and studies of real property values. Through extensive use of SCS computer programs modified for use under urban conditions, the flood-profile information was used to determine average annual floodwater damage by stream reaches.

Concurrently with these studies, numerous steering committee meetings were held on a subwatershed basis to determine project goals. Once these goals were established and the detailed floodwater damage information was available, the process of project formulation began. Numerous alternative solutions to problems could now be examined. Again, SCS computer programs allowed rapid evaluation so that those alternatives with the most potential could be presented to the steering committee. The plan finally selected represents the steering committee's choice of those alternatives which most closely approach meeting the committee's goals and yet may be implemented under the author of PL-566. Of the 10 committee identified goals, six are fully implementable under PL-566.

These relate to reduction of erosion, stream fishery improvement, and floodwater management. The remaining four, relating to water quality standards, recreation, public open space, and wildlife habitat, are partially implementable through PL-566.

During plan formulation, it became apparent that solving floodwater management problems in the Little Calumet Watershed would require innovative measures. While floodwater storage in many parts of the country is conventionally generated by damming stream valleys, this was clearly not a feasible alternative here. Valley characteristics preclude providing significant storage without flooding large areas. With high land values and intensive development, this was clearly not feasible. However, large storage volumes could be attained by using an existing rock quarry and sand pit which were situated in favorable locations relative to damage areas. Two other reservoirs could be provided by excavation of vacant flood-plain areas.

There are several advantages to the excavated below-ground reservoir. First, it uses a relatively small amount of land, and since the need for storage is relatively infrequent (2-yr–5-yr frequency), the land may be used for other purposes such as recreation with no conflict to the flood-control function. No downstream hazard is imposed, since water is not stored at an elevation higher than the flood plain. Additionally, no extra storage or "free board" is required to protect the structural integrity of the reservoir. If the design capacity of the reservoir is exceeded, the surrounding area floods and the reservoir becomes a part of the flood plain. Structural protection is required only for the hydraulic structures regulating inflow.

There are also disadvantages to the excavated reservoirs although they are outweighed by the advantages, e.g., groundwater inflow and direct precipitation must be pumped from the reservoirs thereby contributing to operation and maintenance costs. Contamination of adjacent groundwater may occur during flood storage. However, upon reservoir drawdown, positive groundwater inflow is restored, thus flushing the system and preventing significant contamination. Additionally, the glacial deposits into which the majority of reservoirs are excavated do not provide useable aquifers, thus further minimizing the problem.

The Little Calumet Plan is closely coordinated with existing programs for floodwater management. Of primary importance is the Illinois Department of Transportation, Division of Water Resources Regulation of Construction within the Little Calumet River Watershed (1). This program, which utilizes the flood-plain maps and profiles developed for the Watershed Plan, is in fact a prerequisite for project implementation, since flood-plain regulations are required to be in effect before federal funding. The National Flood Insurance program administered through the Flood Insurance Administration in connection with Housing and Urban Development (HUD) and in cooperation with the Illinois Division of Water Resources is also in effect in the watershed. The combined sewer area of the watershed which will be served by the Tunnel and Reservoir Plan (TARP—MSDGC) is considered to contribute no runoff, since all drainage will be conveyed to subsurface mined-rock storage areas. The Thornton Quarry will be partitioned to serve as reservoirs for both TARP and the Little Calumet Plan (Structure 84—Thornton Reservoir).

A debris removal project along the main stem of the Little Calumet River, recently completed by the Corps of Engineers, was considered in project

evaluation. In the Indiana portion of the watershed, the Corps' 1973 Interim Review Report recommendation of channel improvement for flood control, recreational navigation, and recreation, is considered to be the recommended plan for water resource development as supported by the State of Indiana.

Project formulation was also coordinated with on-site detention requirements of the MSDGC Sewer Permit Ordinance (2) and local ordinances for control of runoff from urbanizing land. The status of local erosion and sediment discharge control ordinances was also considered in project formulation. The planned land treatment program includes technical assistance to local government in establishing these ordinances.

In addition to the benefits or favorable economic impacts, the project will have the following favorable environmental impacts:

1. Improves esthetic qualities of the areas by reducing erosion and sedimentation in streams, lakes, and reservoirs.
2. Reduces sediment leaving urban construction sites from an average rate of 11 tons/acre–2 tons/acre annually.
3. Reduces erosion on agricultural and idle land from an average rate of 8.4 tons/acre–3.8 tons/acre annually.
4. Prevents 52,700 tons of sediment from entering streams each year.
5. Increases and improves wildlife habitat.
6. Reduces the level of suspended solid concentration in streams and lakes.
7. Provides resource data so that urban development can be compatible with resource limitations.
8. Provides for the removal of debris from 109 miles of stream channel.
9. Reduces the area subject to flooding from 10,800 acres to 4,900 acres.
10. Protects 6,615 residences and 142 businesses from flooding.
11. Reduces peak flood discharges from Midlothian Creek, Thorn Creek, North Creek, and the Little Calumet River.
12. Reduces the frequency of flow reversals on the Calumet and Little Calumet Rivers, thereby decreasing potential flow of wastes into Lake Michigan.
13. Augments stream flow by approximately 4,000 gal/min as a result of pumping groundwater from floodwater retarding structures.
14. Preserves and improves esthetic qualities of 107 miles of stream.
15. Creates 12.7 acres of permanent water providing aquatic habitat.
16. Creates 78.6 acres of water surface which will provide waterfowl habitat until displaced by sediment accumulation.
17. Provides 345 acres of public open space.
18. Enhances existing channel ecosystems along 107 miles of stream.

The sponsors of the Little Calumet River Watershed Plan are actively working toward implementation, although federal funding is still 1 yr–2 yr in the future. They recognized that their position before congressional committees will be enhanced if they have in fact demonstrated their support by moving ahead with local responsibilities. Through a Preliminary Land Acquisition Memorandum of Understanding, the MSDGC has agreed to provide up to $7,500,000 toward acquisition of the four reservoir sites. Cook County will provide $250,000 toward acquisition, and the Village of Tinley Park and the Tinley Park District have already acquired 45 acres of the needed 118 acres for Multiple-Purpose Structure

32. It is anticipated that three of the reservoir sites will be fully acquired prior to Congressional funding of the project.

The Will-South Cook Soil and Water Conservation District is working on an active program of land treatment in the watershed. It reports that 42% of the watershed is now adequately treated for erosion control. This represents a significant step toward the 75% required before implementation of structural measures.

The seven sponsors have now signed the Watershed Plan Agreement, an important document in that it shows the intent and responsibility of each of the local sponsors. The plan is now ready for presentation to the House and Senate Public Works Committees for approval after review by the Water Resources Council and the Office of Management and Budget. The chief of the SCS may authorize it for construction following Congressional approval. After detailed project agreements are executed for specific structural measures, and after the sponsors satisfy requirements for erosion and sediment control and nonstructural measures, construction may proceed.

Long-Term Implementation

The Upper Salt Creek Watershed Project is now authorized for construction, and the SCS recently approved a project agreement for $3,800,000 covering construction of Floodwater Reservoir Number 5. The sponsors of the Little Calumet River Watershed Plan are actively seeking PL-566 funding, and in August 1978, SCS approved federal planning assistance for the Lower Des Plaines Tributaries Watershed. For the North Branch Chicago River Watershed, implementation is proceeding through preparation of a Phase 1, General Design Memorandum by the Corps of Engineers. Poplar Creek and Calumet-Sag Channel Watersheds, where floodwater damages are not serious, do not require extensive structural measures. The Illinois Division of Water Resources is now implementing flood-plain regulations and small-scale structural measures in these watersheds in cooperation with local government.

Conclusions

The Chicago Metropolitan Area River Basin Planning effort has been unique in terms of scope, public participation, and agency cooperation. Progress to date indicates that multiple-objective water-resource management plans satisfying federal funding requirements can be implemented in urban areas. The key to plan success lies with effective public involvement through broad-based watershed steering committees.

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BUREAU OF RECLAMATION PLANNING: ENVIRONMENTAL FACTORS

By James E. Price,[1] A. M. ASCE and Leonard Ortolano,[2] M. ASCE

INTRODUCTION

The Bureau of Reclamation (referred to herein as "the Bureau" and recently renamed the United States Water and Power Resources Service) is a Federal agency with responsibilities for planning and implementing multipurpose water-resources development projects in the 17 western states. Two recent mandates have required the Bureau to generate a considerable amount of information concerning "environmental" factors while carrying out its water-resources planning: The National Environmental Policy Act of 1969 (NEPA) requires the preparation of Environmental Impact Statements (EIS), and the U.S. Water Resources Council's (8) "Principles and Standards" require water resources agencies to consider both environmental quality and national economic development as planning objectives.

This paper summarizes results from a research project that focused on the identification of the practices and procedures through which planners have been the most effective in increasing the consideration given to environmental concerns in planning and decision-making (7). In this research, "environmental" concerns are considered to include everything except economics, engineering concerns, and traditional missions of the Bureau, such as irrigation and power generation. Thus, both the natural and social environments are considered.

The research approach involved determining the extent to which various

[1]Research Analyst, Calif. Public Utilities Commission, San Francisco, Calif.; formerly Grad. Research Asst., Dept. of Civ. Engrg., Stanford Univ., Stanford, Calif. 94035.

[2]Assoc. Prof., Program in Infrastructure Planning and Management, Dept. of Civ. Engrg., Stanford Univ., Stanford, Calif. 94035.

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hypotheses suggested by previous, related research (see, e.g., Ref. 6) on the Corps of Engineers and the Soil Conservation Service are relevant to the planning of water-resources projects by the Bureau. These hypotheses were put in operational terms and subjected to testing in 29 case studies of planning investigations carried out in 12 Bureau offices.

Bureau of Reclamation Planning Process

The process currently (1979) utilized by the Bureau for planning new water-resources projects generally involves four principal parts: (1) An appraisal investigation; (2) a feasibility investigation; (3) the review and authorization of a proposed plan; and (4) reevaluation and completion of planning for an authorized project (referred to herein as a "definite-plan investigation"). Appraisal investigations are performed when an intermediate planning step is required between so-called "framework studies" (e.g., river basin plans), and feasibility investigations. Appraisal investigations deal with needs projected for 15 to 25 years in the future, and normally require 2 years or less to complete. Analysis is based primarily on existing data.

Feasibility investigations deal with needs projected for 10 to 15 years in the future, and require 3 years or less to complete. In feasibility investigations, multiobjective planning is implemented in detail, using an iterative plan formulation process that is consistent with the Water Resources Council's "Principles and Standards." This process emphasizes the development of more than one viable alternative plan and the involvement of the public in planning. The formulation and evaluation of alternative plans is generally an iterative process in which the alternative plans are progressively refined and new alternatives, which often represent compromises between earlier alternatives, are formulated and evaluated. The plan formulation process typically yields a plan emphasizing the national economic-development objective, a plan emphasizing the environmental-quality objective, and one or more plans that are in some sense intermediate between the two. The level of detail of feasibility investigations must be sufficient to allow the planning officer of the Bureau region in which the study area exists to compare the alternative plans and select the most appropriate one (10).

Unless local sponsors will reimburse the total costs of a project, Congress must authorize the project prior to construction. Normally, a project proposal (as contained in a feasibility report) goes through a process of review by other Federal and state agencies and officials before it is authorized. Following an extensive administrative review, the Secretary of the Interior Transmits the feasibility report along with his recommendation to the President (through the Office of Management and Budget). After further administrative review, the Secretary of the Interior transmits the report and its associated review documents to Congress for authorization for construction. Authorization is complete when a bill has been passed in final form by both the House and Senate and signed by the President. Funds for project construction are provided by acts that are separate from project authorization (2,13).

Following project authorization, the definite-plan investigation is carried out to review the proposed plan of project development, resolve any remaining questions with respect to the plan, make necessary revisions required by events

that occur subsequent to preparation of the feasibility report, and develop the information required for the preparation of final designs and specifications for construction. Public participation is generally less extensive during definite-plan investigations than it is during feasibility investigations. The activities included in definite-plan investigations vary with the particular conditions surrounding the associated projects. The most important differences between feasibility and definite-plan investigations are that: (1) Only feasibility investigations are governed by the United States Water Resources Council's "Principles and Standards," and (2) only definite-plan investigations have a recommended plan that exists at the outset of the investigation.

Research Design

Because the key mandates requiring the consideration of environmental factors in planning investigations have been implemented only in the past few years, and because the time required to carry a project planning study from the appraisal investigation through the definite-plan investigation can take many years, two types of ongoing and recently completed Bureau planning investigations were examined: feasibility investigations and definite-plan investigations. The research included a total of 18 feasibility investigations and 11 definite-plan investigations, and this represents approximately 80% of the planning studies having been conducted recently enough to have been influenced by planning procedures reflecting the National Environmental Policy Act (NEPA) and the Water Resources Council's "Principles and Standards" and having been already completed or nearly completed. (These planning investigations are referred to herein as case studies.)

A "dependent variable" was defined and measured for a sample of planning studies in each of these two groups. For the feasibility investigations, the dependent variable represents the influence of environmental information on the formulation of alternatives (referred to herein as the "formulation variable"). This variable reflects: (1) The number of environmental objectives and constraints considered in the formulation of alternatives, relative to all objectives and constraints; and (2) the influence of "environmental advocates" on the outcomes of planning tasks related to "problem definition" and the formulation of alternatives. (These "advocates" include the Bureau's environmental specialists, environmental interest groups, the general public, and governmental agencies other than the Bureau and eventual users of the project.) For the definite-plan investigations, the dependent variable represents the influence of environmental information on the modification of the plan authorized by Congress before the initiation of the definite-plan investigation (referred to herein as the "modification variable"). This variable reflects: (1) The extent to which the Congressionally authorized plan is modified (during the definite plan investigation) to reduce adverse effects of the authorized plan on selected environmental resources; and (2) the influence of the aforementioned environmental advocates on the outcomes of planning decisions made during the definite plan investigation.

Formal a priori hypotheses concerning circumstances that might lead to increasing the influence of environmental considerations were formulated on the basis of findings from previous, related research efforts at Stanford University; this previous research is summarized by the second writer (6). These hypotheses take the form of "independent variables" which, when increased, are expected

to increase the "influence of environmental factors," i.e., the value of the dependent variables. The independent variables are categorized into four variable groups as follows: organizational design, attitudes, external coordination, and timing.

The research involved testing the a priori hypothesis by measuring the variables for each of the planning investigations included in the research, and then analyzing the results to see if the scores are consistent with what would be expected if the hypotheses were true. The principal source of data used in measuring the variables consisted of interviews with the following two people for each planning investigation: (1) The person who played the key role in coordinating the engineering and economic aspects of the planning study, referred to herein as the "planning leader"; and (2) the person who coordinated the environmental aspects of the planning study, referred to herein as the "environmental specialist." The interviews were built around a structured, pretested interview schedule and typically lasted several hours per planning investigation. The interview data was supplemented by data obtained from planning documents and from follow-up letters and telephone conversations which cleared up any ambiguities that remained after the interviews had been conducted.

The procedures for scoring the dependent and independent variables are such that it is often possible only to rank order the planning investigations in each of the two samples with respect to a given variable. Thus, e.g., it is possible to say that planning investigation A scored higher than planning investigation B, but it is not possible to say that it scored "X times" as high. To examine relationships between variables of this type, it is appropriate to use nonparametric statistical procedures. One such procedure, which was widely used in this research, involves the computation of the correlations between the rank order obtained for a dependent variable and an independent variable. The strength of this correlation is reported herein by "Kendall's rank correlation coefficient" τ, and the corresponding level of significance, p; the latter represents the probability of obtaining a given value of τ if, in fact, there is no underlying relationship between the two variables. The rank correlations obtained in this research are considered to be "statistically significant" if $p \leq 0.10$. The scoring procedure for some of the independent variables involves only two possible scores (e.g., "yes" or "no"). In these cases, the "Mann-Whitney exact test" is appropriate to analyze the nature of the relationship between the dependent and independent variables. Details regarding these statistical procedures are given by Siegel (12).

The research results reported herein are determined through a combination of statistical data analysis, compilation of observations made during interviews for the 29 case studies, and anecdotal knowledge of the individual case studies. In the interests of brevity, only a few of the hypotheses tested are presented herein; the ones presented correspond to some of the highest correlations achieved between dependent and independent variables. A more complete description of the research design and a more detailed presentation of research results is given by the writers (7).

Multidisciplinary Planning Versus Interdisciplinary Planning

The Council on Environmental Quality's 1973 guidelines for implementing

NEPA recognize NEPA's Section 102(2)(A) requirement that Federal agencies "utilize a systematic interdisciplinary approach" to impact assessment, and caution that an interdisciplinary approach should be used in planning as well. The use of interdisciplinary planning requires more than using planners who are trained in a variety of disciplines. As examined by Dorsey and Fox (1), interdisciplinary planning can be distinguished from multidisciplinary planning as follows: Individuals working in a multidisciplinary effort may pursue different objectives which are loosely related to one another, whereas participants in an interdisciplinary effort endeavor to utilize their individual theories and methodologies in an integrated effort to achieve a common project objective.

Several aspects of the hypotheses tested in this research concern the three traits which Hill (3) argued should be observed if interdisciplinary planning is occurring, namely: (1) Group meetings in which all disciplines are represented; (2) participation of environmental specialists in the formulation of alternatives; and (3) a high degree of informal coordination and communication between engineering planners and environmental specialists. The findings of the research are reviewed in the following in the context of these three traits. Observe that the measurement of interdisciplinary planning was not a part of the original research design, and so it is not appropriate to state conclusions regarding its importance in increasing the consideration given to environmental factors. The concept is nonetheless useful, however, in interpreting some of the principal findings regarding the consideration of environmental factors in Bureau of Reclamation planning investigations.

Use of Group Meetings.—The Bureau's *Reclamation Instructions* (10) specify that planning teams will be used during all feasibility investigations. These planning teams met as a group in 17 of the 18 feasibility investigations included in this research, and an environmental specialist was a member of each of these teams. The one feasibility investigation that did not involve a planning team received the lowest score on the formulation variable (i.e., the dependent variable measuring the extent to which environmental information influenced the formulation of alternative plans). Because there is so little variation in whether or not planning teams are used in feasibility investigations, it is useful to examine the frequency of planning-team meetings. Although the *Reclamation Instructions* specify that planning teams will be used in all feasibility investigations, they do not specify the number of times that a planning team should meet. A positive rank order correlation is observed between the frequency of planning-team meetings and the influence of environmental factors on the formulation of alternatives ($\tau = 0.40$; $p = 0.02$). This supports the notion that the influence of environmental factors on the formulation of alternatives increases as environmental specialists participate as members of teams that are active, where team activity is reflected by the frequency with which teams meet.

Planning teams that met as an entire group and that included environmental specialists as members were used during only five of the eleven definite-plan investigations included in the research. Although these five investigations achieve higher modification variable scores than the six studies for which no planning team of any kind met, the difference in scores is not great enough to be statistically significant at the 0.10 level (Mann-Whitney exact $p = 0.16$).

Expected Duties of Environmental Specialists.—The second of the three traits that Hill (3) indicates would be expected if interdisciplinary planning were being

carried out is the participation of environmental specialists in the formulation of alternatives. The research includes an a priori hypothesis which suggests that the influence of environmental information on the formulation of alternatives will increase if the duties of environmental specialists include a broad range of activities concerning the formulation and evaluation of alternatives, rather than specific, narrowly defined tasks concerning the preparation of legally adequate EIS. Analysis of this hypothesis relies on interview questions asking planning leaders to indicate the three most important duties that they expect of environmental specialists, and asking environmental specialists to indicate the three most important duties they believe planning leaders expect of them.

The answers to the aforementioned questions were examined to determine whether the environmental specialist was expected to perform each of the following duties: (1) Identification of project objectives; (2) identification of constraints on project planning; (3) formulation of alternatives; (4) impact assessment; (5) plan selection; (6) public participation; (7) interagency coordination; (8) development of baseline data; and (9) review of the work of others. The responses from the interviewees provide a basis for constructing two "breadth of duties" indexes, i.e., one representing the breadth of duties that planning leaders expect of environmental specialists and one representing the breadth of duties that environmental specialists believe planning leaders expect of them. High scores on these indexes are received when large numbers of the duties listed above are expected; these high scores are interpreted as an indication that the environmental specialist was not restricted to examining issues that focused only on the environment. If the a priori hypotheses were true, then it could be expected that planning investigations that receive high scores on the "breadth-of-duties" index would also receive high scores on the dependent variables.

The data gathered for feasibility investigations supports the a priori hypothesis in several ways. In particular, the rank correlation between the formulation variable and the breadth of duties index based on planning leader responses is $\tau = 0.48$ (with $p = 0.006$). The data analysis indicates that there are several duties that (1) are expected by less than half of the planning leaders, and (2) show a positive and statistically significant relationship with the influence of environmental factors in the formulation of alternative plans. These duties include the following: interagency coordination, definition of constraints, public participation, and plan selection. It seems that the role of environmental specialists in feasibility investigations should be focused on a broader range of activities than is now the case in many investigations.

The statistical tests run for the feasibility investigation data were run for the definite-plan investigation data as well. However, the results are completely different in the sense that virtually no noteworthy correlations with the indexes were determined. In other words, there is no support for the postulated relationship between the influence of environmental information on the modification of a Congressionally authorized project and the extent to which environmental specialists are expected to perform a broad range of duties. The results indicate, however, that one notable duty, which is positively and significantly correlated with the influence of environmental information on the modification of an authorized plan, concerns "the review of plans developed by others" (Mann-Whitney exact $p = 0.04$ for planning leader responses).

Although the correlation analysis yielded results that are not consistently supportive of the a priori hypothesis, several impressions gained during the various case study interviews indicate that the specification and perception of the role of the environmental specialist represents a nontrivial issue worthy of careful consideration. One general observation gained in these interviews is whether an environmental specialist functions as an active planner (in contrast to a staff advisor) is important. The consideration of environmental factors is *not* enhanced by restricting the role of environmental specialists to "staff functions," i.e., providing specific input in response to requests made by a planning leader. Environmental information is likely to have a greater influence on planning outcome if environmental specialists are active as planners, and not just staff advisors. The case studies also suggest that the self-motivation of environmental specialists to become involved in all aspects of planning may be an important factor in determining the extent to which such specialists influence planning decisions. Unfortunately, this suggestion can only be inferred from related results because the measurement procedures utilized in this research were not designed to provide a direct assessment of environmental specialists' motivation to become involved in all aspects of planning.

Communication between Engineering Planners and Environmental Specialists.—The third of the traits of interdisciplinary planning described by Hill (3) concerns coordination and communication between engineering planners and environmental specialists. The a priori hypothesis corresponding to this trait states that the influence of environmental information on the formulation of alternatives, and the modification of an authorized plan, will increase if the communication between the planning leader and the environmental specialist encourages the transfer of information between the two. This hypothesis corresponds to Hill's suggestion that interdisciplinary planning is characterized, in part, by a high degree of informal coordination and communication between engineering planners and environmental specialists. The interviews with planning leaders and environmental specialists included questions asking respondents to indicate, using 5-point scales, the extent to which each of several conditions prevailed. The hypothesis was tested by constructing indexes using the responses gathered for each planning investigation included in the research; these indexes represent the extent to which the communication between the two respondents encourages the transfer of information between them. The indexes are computed by counting the number of the following attributes of communication that the respondents reported as characterizing their communication. For the data collected, this index consists of the following characteristics:

1. Respondents rely at least "almost always" on informal relationships and interaction.
2. Verbal or written communication occurs at least once a day.
3. At least 40% of communication is innovation-oriented.
4. Feedback is requested at least three-fourths of the time.
5. Feedback is provided at least three-fourths of the time.

There are positive and statistically significant correlations between both dependent variables and the indexes based on both planning-leader and environmental-specialist responses. For both dependent variables, these results are

consistent with what would be expected if the a priori hypothesis were true. To further explore this finding, correlation coefficients were computed for each of the five attributes that was included in the indexes. For the feasibility investigations, the individual items for which either or both of the respondents' answers have positive and statistically significant rank correlations with the formulation variable are the use of informal relationships, a high frequency of communication, and an orientation towards innovation. Indeed, an emphasis on frequent, informal interactions might be expected during early stage of planning, and this is supported by the observed correlations with the formulation variable. In sharp contrast, the two feedback items played a central role in terms of statistically significant correlations with the modification variable. This reflects the importance of the review of previous plans as being a principal part of definite-plan investigations.

Should Planning Be More Interdisciplinary in Nature?—The foregoing examination focuses on three traits which Hill (3) has argued should be observed if interdisciplinary planning is occurring: (1) Group meetings in which all disciplines are represented; (2) participation of environmental specialists in the formulation of alternatives; and (3) a high degree of informal communication between engineering planners and environmental specialists. Using these three traits as a crude guideline for saying that interdisciplinary planning did or did not take place, the research results suggest the following: Of the two samples of planning investigations included in the research, the only sample for which interdisciplinary planning was being carried out to any noteworthy extent is the feasibility investigations. Moreover, for this sample, the planning investigations that received high scores on the formulation variable generally received relatively high scores on the independent variables that were used to measure Hill's three traits. For the feasibility investigations, these results provide the basis for the following a posteriori hypothesis that could be subjected to future testing: the influence of environmental information on the formulation of alternatives will be increased if an interdisciplinary planning framework is employed. In research such as that discussed herein, it is inappropriate to test the validity of an a posteriori hypothesis using the same data set that originally suggests the hypothesis. In order to test this a posteriori hypothesis, it would be necessary to provide an operationally meaningful measure of the extent to which interdisciplinary planning occurs during any given study, and then to implement the measurement procedure for the relevant planning investigations included in the research. Future studies could use Hill's three traits as a starting point in constructing a measure of interdisciplinary planning. The previously mentioned distinction between interdisciplinary and multidisciplinary planning offered by Dorsey and Fox (1) suggests that the sharing of common goals among participants in planning could be considered as a fourth trait of interdisciplinary planning.

For definite-plan investigations, the research results do *not* provide the basis for any a posteriori hypothesis regarding interdisciplinary planning. Indeed, the results, together with qualitative impressions gained from the case study interviews, suggest that (using Hill's three traits as a definition) there were only a small number of the 11 definite-plan investigations in which interdisciplinary planning had taken place. Planning teams were used in less than half of the 11 case studies, and the formulation of alternatives was an expected duty of environmental specialists in only a few of these studies. With their emphasis

on the "review of plans," most definite-plan investigations seemed to be carried out using a multidisciplinary (as opposed to an interdisciplinary) planning framework.

Alternative Organizational Structures

The research also explored other characteristics of planning investigations that were believed to promote effective consideration of environmental factors. One of the a priori hypotheses examined in the research indicates that the influence of environmental information on the formulation of alternatives, and

TABLE 1.—Relationships between Dependent Variable and Alternative Organizational Arrangements

Category number (1)	Organizational arrangement (2)	DISTRIBUTION OF CASES					
		Formulation Variable			Modification Variable		
		Low scores (3)	Middle scores (4)	High scores (5)	Low scores (6)	Middle scores (7)	High scores (8)
1	Regional Office: Planning leader and environmental specialist in Division of Planning	3	2	1	2	0	0
2	Regional Office: Planning leader in Division of Planning, environmental specialist outside Division of Planning	2	2	2	0	2	0
3	Field Office: Environmental specialist on planning staff	0	2	2	1	1	3
4	Field Office: No environmental specialist on planning staff	2	0	0	0	0	0

on the modification of an authorized plan, will increase if the relative organizational positions of the planning unit and the unit containing the environmental specialist(s) lend greater authority to the environmental specialist(s). In case studies of water resources planning in two Corps of Engineers district offices, Randolph (9) suggests that somewhat greater influence on the planning process is exerted by an environmental unit that is separate from (but on an equal level with) the planning unit, than by one that is contained within the planning unit. If Randolph's finding is applied to the Bureau, one would expect to find that the influence of environmental factors on planning outcomes would be greater in Bureau offices in which the environmental unit is separate from (but at the same level in the office hierarchy as) the planning unit.

Alternative Locations for Environmental Specialists.—Project planning in the Bureau is conducted through seven regional offices. There are additional field

offices under the regional offices, and some of these also plan projects. Organizational differences exist between the Bureau's seven regions in the conduct of environmental work, and the regions themselves currently place planners in as many as three geographical locations, each with slightly different organizational arrangements.

The analysis of the relative positions of environmental units and planning units in Bureau offices is complex because of the wide variety of organizational structures of the different regional and field offices. To examine the hypothesis, the organizational arrangements used in most planning investigations were grouped into the four categories shown in Table 1. Observe that the columns in Table 1 are divided into two main groups corresponding to the two dependent variables. Within each group, the case studies are further divided into three parts based on "cutpoints" in the dependent variable scores that (1) place roughly the same number of investigations in each range of scores, and (2) appear consistent with overall impressions gained from the case study interviews.

Because the a priori hypothesis relates only to the types of organizational arrangements found in the regional offices, only the first two rows of Table 1 are relevant to hypothesis testing. These data indicate that there is no support for the portion of the a priori hypothesis that concerns the formulation of alternatives. There is, however, some support for the portion of the a priori hypothesis that concerns the modification of an authorized plan. The two definite-plan investigations conducted in regional offices and using an environmental specialist located *outside* the Division of Planning receive higher modification variable scores than the two investigations conducted in regional offices and using an environmental specialist located *within* the Division of Planning. Although the level of statistical significance associated with this relationship is only $p = 0.17$, that is the lowest level attainable if the sample size used in the Mann-Whitney test is only 4.

Alternative Roles of Environmental Specialists.—The lack of strong support for the portion of the a priori hypothesis concerning the formulation of alternatives can be explained by an argument proposed by Jenkins and Ortolano (4): Environmental specialists perform several different roles in planning investigations, and no single organizational location is appropriate for conduct of *all* of these roles. Planning, report preparation, report review, and coordination with outside environmental spokesmen and hired consultants are relevant activities in feasibility investigations. Jenkins and Ortolano argue that the planning role of environmental specialists is highly interdependent with the engineering and other tasks (e.g., economic evaluations) that are associated with water-resources planning because the output of engineering planners and environmental specialists become input for each other; the placement of environmental specialists *within* the Division of Planning of a regional office facilitates the task integration and coordination (e.g., scheduling of work) necessary between environmental specialists and others involved in those tasks. In contrast, there is a high degree of "differentiation" between the tasks of those engaged in the preparation and review of environmental reports. (Tasks are said to be differentiated when differences in orientation or outlook are required in their performance.) The report preparation and review roles require a high degree of objectivity in making environmental assessments that may be critical of plans developed by the Division of Planning; environmental specialists *outside* of the Division of Planning can

be more effective in providing this type of objective assessment. The argument here is that environmental specialists within the Division of Planning would be less objective in providing assessments of plans that they helped to develop. Moreover, in instances where environmental specialists outside the Division of Planning differ with engineering planners, these specialists at least have the option of referring these differences to a higher level in the regional office hierarchy. While such hierarchical referral may not be used frequently, the option of using it is felt to be significant (4). Thus, for feasibility investigations, there is no single location for environmental specialists that increases the effectiveness of all of the various roles played by such specialists. The data for feasibility studies in Table 1 are consistent with the perspective that neither category 1 nor category 2 provides, in any complete sense, the best location for environmental specialists.

Jenkins and Ortolano also suggest that it may be preferable to locate environmental specialists in more than one organizational unit. For example, the environmental specialists engaged in the definition of objectives, the formulation of alternatives and other basic planning activities could be located within the Division of Planning, *and* other environmental specialists could be located outside the Division of Planning for purposes of review of plans and reports and for providing an interface between Bureau planners and outside environmental spokesmen. This would make it possible to obtain good coordination and integration of environmental perspectives on routine planning activities *and* a critical in-house review of the planning effort by the environmental specialists outside of the Division of Planning. Alternatively, environmental specialists located outside the Division of Planning could perform basic planning activities as well as providing coordination with outside environmental interests, while one or more environmental specialists within the Division of Planning could provide in-house review and coordination of plans and reports. The theoretical arguments underlying this suggestion are supported by two particular case studies in which the environmental specialists who were located both inside and outside the Division of Planning played active roles in the planning investigations.

The advantages of locating environmental specialists outside the Division of Planning are clearer for definite-plan investigations than for feasibility investigations. For definite-plan investigations there is much less emphasis on planning (in the sense of formulating new plans) and a much greater emphasis on report preparation and coordination with outside environmental spokesmen. There are some clear advantages for having report preparation and review performed by environmental specialists in a unit that is separate from the Division of Planning. In addition to the ability to make hierarchical referrals and increased objectivity in report preparation, a separate unit for environmental specialists can be useful in facilitating coordination, i.e., liaison efforts with outside environmental spokesmen. These advantages provide a partial explanation for the results in Table 1 that show category 2 definite-plan investigations as having higher scores on the modification variable than those in category 1.

Another interesting aspect of the research results concerning organizational design issues centers on the use of field offices vis-a-vis regional offices for conducting planning investigations, i.e., categories 3 and 4 in Table 1. First consider category 4; the data in Table 1 suggest that this organizational arrangement, in which the engineering planners are in field offices but the environmental

specialists are in regional offices, is not very effective as a means of incorporating environmental factors into planning. In contrast, the data for category 3 (i.e., investigations in which engineering planners and environmental specialists are together in field offices) show that this arrangement is generally associated with higher scores in the dependent variable than *any* of the organizational arrangements represented by the other categories. Because the importance of field offices was not recognized at the outset of the research, no a priori hypothesis concerning them was tested. However, the research results suggest that it may be worth investigating this subject further in future research.

Coordination with Other Agencies and Public

Other findings of the research regarding the influence of environmental information on planning outcomes demonstrate the value of an "open" planning process that actively seeks external input on project-related environmental issues. Some of the strongest positive, statistically significant relationships are found between the dependent variables and the variables characterizing the involvement in the planning process of other agencies, environmental interest groups, and the general public. These relationships are consistent with general impressions gained through the field interviews, namely, that external coordination provides an important source of information concerning the environmental aspects of project planning.

Commitment to Obtaining External Input.—The Bureau utilizes a process for external coordination that consists of two parallel activities: (1) Technical studies to obtain substantive in-depth participation by spokesmen for specific interests; and (2) public involvement to assure that a broad range of interests have a general opportunity to participate (11).

Technical studies during feasibility investigations are organized around a planning team, which always includes Bureau employees. In addition, planning teams often include personnel from other agencies and sometimes include representatives from interest groups and the general public, or individuals knowledgeable about the project area, such as university professors. Subteams are often used to provide specialized inputs to the main planning team.

To secure a broad base of public participation, the Bureau uses public meetings and advisory committees. Informal public meetings (rather than formal public hearings) are used to communicate with the general public; advisory committees consist primarily of representatives from private citizens groups and from local and state governments (11). In practice, the roles of advisory committees sometimes overlap with the roles of planning teams, and a wide variety of different names are used in referring to such groups. For these reasons, the following definitions are utilized herein to distinguish between the two types of bodies: Planning teams are groups that participate in analysis of issues specifically related to an investigation. Advisory committees are groups that provide advice on issues specifically related to an investigation, organized by a body that does not dominate the committee in membership.

One a priori hypothesis states that the influence of environmental information on the formulation of alternatives, and the modification of an authorized plan, will be increased if the project planners exhibit a greater commitment to obtaining external input. The results of testing this hypothesis are considered in the following

for the two samples of planning investigations included in this research.

First consider the sample of feasibility investigations. One set of measures used to examine Bureau planners' commitments to obtaining external input relates to aspects of the use of public meetings, planning teams, and advisory committees. Although the few feasibility investigations that did not include *any* public meetings receive significantly lower scores on the formulation variable than investigations during which public meetings were held, there is no statistically significant correlation between the formulation variable and the *number* of public meetings held in each investigation. The data suggest that the use of planning teams and advisory committees plays a more important role than public meetings in terms of increasing the influence of environmental considerations in the formulation of alternatives. For many feasibility investigations, the planning team served as a principal mechanism for maintaining ongoing coordination with representatives from other agencies and environmental interest groups, who served as full-fledged team members. Statistically significant positive correlations are observed between the formulation variable and the frequency of planning team meetings (i.e., a simple count of the number of meetings held; $\tau = 0.40$, $p = 0.02$) and the breadth of membership of planning teams (i.e., the variety of members from Federal, state, and local agencies, environmental interest groups, etc.; $\tau = 0.34$, $p = 0.03$). Data analysis suggests that there is also a positive relationship between the formulation variable and the breadth of membership in advisory committees, but this relationship is apparently less important than the relationship between the formulation variable and characteristics of planning teams.

One aspect of the Bureau's use of planning teams that was not recognized at the outset of this research and, consequently, was not included in the conceptual definition of commitment to obtaining external input, concerns the use of multiple planning teams and/or subteams. During some feasibility investigations, a single planning team is used for all technical analysis and decision-making. In other investigations, two or more coequal planning teams are used, or subteams and task forces are used to assist a main team on specific issues such as recreation or fish and wildlife. The use of these specialized subteams can increase the effectiveness of planning teams by allowing participants with specific interests to concentrate on their own areas of special expertise without being distracted by other problems. This increase in effectiveness is reflected in a positive rank correlation between the formulation variable and the total number of teams that perform technical analysis of planning issues and assist in decision-making ($\tau = 0.30$, $p = 0.05$). A more thorough analysis of the wide variety of arrangements of multiple planning teams and subteams used in Bureau planning is a subject that seems worthy of further research.

Next consider the sample of definite-plan investigations. For these studies, the data indicates that the influence of environmental information on the modification of a proposed plan is greater when at least one large, informal public meeting is held during the investigation. (Mann-Whitney exact $p = 0.07$.) In addition, a statistically significant correlation occurs between the modification variable and the number of public meetings held in each investigation ($\tau = 0.32$, $p = 0.09$). It appears that public meetings play a more significant role in the consideration of environmental factors in definite-plan investigations than they do in feasibility investigations. (Advisory committees and planning teams

that include members from outside the Bureau were not widely used in the definite-plan investigations included in this research.)

Generation of New Information.—The case studies reported herein that much new information related to environmental concerns is being generated as a consequence of recent mandates (e.g., NEPA) and their expanded coordination requirements (e.g., the "review and comment" on EIS). Testing of a related a priori hypothesis indicates that this new information is followed by a corresponding increase in the influence of environmental factors on planning outcomes; i.e., the new information yielded by external coordination leads Bureau planners to be more aware of (or attach greater importance to) environmental considerations than if no such new information is received.

In order to test the a priori hypothesis an "index of new information" was constructed on the basis of interview responses from the planning leaders. This index ranges in value from 0 to 7 for each planning investigation, and was constructed by adding one point whenever the planning leaders' responses indicate that: (1) At least "quite a bit of useful input" was received from the public (on a given case-study planning investigation); (2) other agencies offered "many insights" into their views of the investigation; (3) a new objective or constraint was suggested (via external coordination); (4) a new alternative was suggested; (5) new information pertaining to previously identified environmental concerns was suggested; (6) the criticism received was specific; and (7) strong preferences among alternatives were expressed.

The data analysis indicated that rank correlations between these index values and the dependent variables were very strong indeed. For the feasibility investigations the rank correlation between the formulation variable and the index of new information is statistically significant at the $p = 0.01$ level ($\tau = 0.43$) and for definite-plan investigations, the rank correlation between the modification variable and the index of new information is statistically significant at the $p = 0.006$ level ($\tau = 0.72$). Analysis of individual components of the index suggests that the relationship between the dependent variables and input from public participation are stronger than for input from other agencies; this may result because more than 80% of the respondents feel that other agencies have provided at least "quite a bit of useful input" (i.e., there is relatively little variation in the responses concerning inputs from other agencies).

Influence of External Pressure on Planning Outcome.—The notion underlying another hypothesis is that if controversial environmental issues are raised during an investigation, then Bureau planners are likely to take a very careful look at environmental factors to make certain they have been fully accounted for; in so doing, they decrease the prospect of incurring delays occasioned by critics who claim that the requisite environmental studies were not conducted. The correlation between the formulation variable and an index representing the overall level of environmental pressure surrounding a planning investigation is positive and statistically significant ($\tau = 0.26$, $p = 0.08$) and thus supportive of the a priori hypothesis.

The results for the sample of definite-plan investigations also provide some support for the a priori hypothesis. The results show statistically significant positive correlations between the modification variable and pressure from the general public or organized interest groups, and governors or other high-ranking state officials. However, litigation concerning alleged inadequacies in the EIS

prepared during two definite-plan investigations has *not* precipitated any major modification in the proposed plans. These two cases do not achieve notably higher scores on the modification variable than cases that were not the subject of environmentally related litigation. Thus, the data provide no support for the existence of any relationship between litigation (or the threat of litigation) and the influence of environmental information on the modification of an authorized plan. There are clear dangers, though, in making any generalizations regarding the influence of litigation that concerns environmental issues on planning outcomes since only two out of the 29 case studies involved such litigation.

Overall, the findings concerning definite-plan investigations suggest that for projects in the late stages of planning, environmental interest groups may be more effective by employing strategies other than litigation. These alternative strategies involve the formation of alliances between citizen groups and conservation agencies. The citizens groups can be effective by lobbying at high levels of state government (e.g., state governors) and lobbying Federal officials as well; under the recent Council on Environmental Quality (CEQ) (5) regulations governing EIS, the Federal conservation agencies will have a formalized ability to refer matters to CEQ when they feel that significant unresolved controversies exist that demand the attention of CEQ.

Timing of External Coordination and Environmental Studies

An important aspect of external coordination and in-house environmental studies relates to the timing of their occurrence in the planning process. On the basis of past research, several a priori hypotheses were formulated that concerned relationships between the dependent variables and the timing of external coordination and environmental data gathering and analysis. The research examined the timing of these activities in relation to two key decision-making points in the early stages of a feasibility investigation: (1) The point in planning at which the planning leader develops a preference for a single alternative; and (2) the point at which a particular alternative is tentatively selected as the proposed plan. (Note that since an authorized plan exists from the outset of definite-plan investigations, the comparison of timing of external coordination and information gathering activity to the two decision-making points mentioned previously would be less meaningful in such studies. For this reason, the analysis of timing excludes the sample of definite-plan investigations.)

The analysis of interview data concerning timing reveals that the early conduct of external coordination activities relative to decision-making does indeed have a positive and statistically significant relationship to the influence of environmental information on the formulation of alternatives.

A different approach to analyzing the timing of environmental work is to measure the timing of selected environmental analyses relative to the timing of selected engineering and economic analyses. Data analysis following this approach supports the view that environmental problems must be analyzed at least as early as engineering problems if solutions to the environmental problems are to be incorporated into the alternative plans being considered. Although alternative plans are continually refined after their initial formulation, time, manpower, and budget constraints may make it hard to change the alternative plans substantially when much of the analysis of alternatives has been completed.

As the emphasis of the planning work shifts from identifying alternatives to determining whether the alternatives are feasible for implementation, planners become less able to consider new objectives, constraints, and alternatives and still complete the investigation on schedule.

The findings associated with the portions of this research that concern timing provide substantive documentation that supports assertions made by many observers who have advocated that infrastructure planning agencies give increased consideration to environmental factors. Indeed, the results of the research concerning timing provide formal support for the emphasis on the early initiation of external coordination and environmental studies that is contained in the recent CEQ regulations for the implementation of NEPA.

Summary and Conclusions

The research findings discussed above suggest several ways in which the increased consideration of environmental factors in Bureau planning and decision-making might be achieved. In feasibility investigations, environmental information is likely to have a greater influence on planning outcomes if an interdisciplinary planning process is used; this involves: (1) Active use of planning teams which include environmental specialists as members; (2) participation of environmental specialists in a broad range of planning tasks, such as the formulation of alternatives; and (3) a high degree of informal coordination and communication between engineering planners and environmental specialists. In contrast, for definite plan investigations, the key duties for environmental specialists appear to concern the review of proposed plans. The task of plan review may be best served by (1) Placing environmental specialists outside the Division of Planning; and (2) ensuring continual two-way communication between engineering planners and environmental specialists.

The significance of coordination between Bureau planners and other agencies and segments of the public cannot be underestimated. A commitment to obtaining external input of information represents the Bureau's responsibility in external coordination activities. Other agencies and segments of the public can be considered as having the responsibility of responding to the Bureau's external coordination efforts by providing inputs of information relevant to the Bureau's planning activities. During early stages of planning, an effective strategy for outside interests consists of taking advantage of all opportunities for involvement in the planning process. In feasibility investigations, the key activities include participation in planning teams and advisory committees, and in definite-plan investigations, the key activities involve public meetings. In late stages of planning, the most effective strategy for outside interests may be the formation of alliances between citizen groups and conservation agencies rather than environmental litigation. The citizen groups can be effective by lobbying at high levels of state government and lobbying federal officials as well; under the new CEQ regulations implementing NEPA (5), the federal conservation agencies have a formalized ability to refer unresolved controversies to CEQ.

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JOURNAL OF THE WATER RESOURCES PLANNING AND MANAGEMENT DIVISION

PLANNING FOR DROUGHT: A MANAGEMENT PERSPECTIVE[a]

By James E. Crews,[1] M. ASCE

INTRODUCTION

The nation's capital and surrounding environs in both Maryland and Virginia face potentially severe water shortages in the future. A growing population and economy, centered around the Federal government, are placing increasing demands on the existing water supply systems. The water supply problem has manifested itself both historically and presently. The Metropolitan Washington Area (MWA) generally depends on the Potomac River for most of its supply, and hydrologic history has shown this supply to be highly variable, subject to both floods and droughts. Serious droughts, such as those of the 1930s and 1960s are characteristic of the Potomac's response to extreme dry weather. Water supply withdrawals from the river have been known to exceed the recorded low flow. Since 1971, demands placed on the river have exceeded the recorded low flow of 388 million gallons per day (mgd) (1.5×10^6 m^3/day) 41 times. In addition, localized water shortages have been experienced. In July 1977, a water shortage caused by a fire in a pump station affected 1,200,000 residents in Maryland and prompted an emergency closing of major businesses and industries. Across the river in Virginia, a local reservoir serving 615,000 persons reached a record low in October 1977, prompting calls for increased water conservation. As population continues to increase in the MWA, the risk of shortages will increase likewise.

This is not a new problem; the MWA's water supply has been studied for years with little or no regional cooperation resulting toward implementing

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[1]Chf., Urban Studies Branch, Baltimore Dist., Corps of Engrs., Baltimore, Md. 21203.

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solutions. Institutional problems have overshadowed the need for cooperation. This is evident when the complexity of the Potomac River and the MWA is viewed from the regulatory permitting authority, multistate interest combined with local interest, and the presence of the seat of government.

The Congress, by its actions, has assumed a lead role for regional water supply planning by acting through the Corps of Engineers. The Congress, in the Water Resources Development Act of 1974, recognized the potentially critical situation and authorized the MWA Water Supply Study in Section 85 of that Act. The Congress directed the Corps to make a complete investigation of the water resources needs of the MWA, with recommendations for implementation. Outlined as follows is a summary of the Corps' efforts to get the MWA to agree on a regional solution while still maintaining service area independence, a feat not heretofore accomplished.

Setting

The MWA, shown in Fig. 1, is the seventh largest Standard Metropolitan Statistical Area (SMSA), with an estimated population of around 3,000,000.

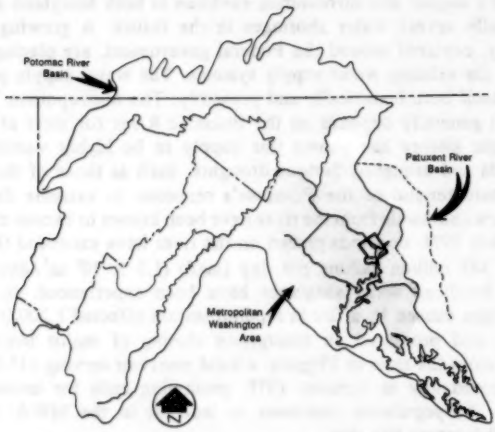

FIG. 1.—Location of Metropolitan Washington Area

The Potomac River provides approximately 70% of the total supply used in the MWA, nearly 400 mgd (1.5×10^6 m^3/day), out of a total 700 mgd (2.7×10^6 m^3/day). The remaining 300 mgd (1.1×10^6 m^3/day) comes from other surface sources and groundwater.

New or expanded intakes have been authorized and are being constructed, creating an even greater demand upon a limited Potomac resource during low flow periods.

Currently, the MWA is served by 25 independent water supply systems; however, the three largest systems—Washington Aqueduct Division (WAD) of

the United States Army Corps of Engineers, Washington Suburban Sanitary Commission (WSSC), and the Fairfax County Water Authority (FCWA)—furnish about 90% of the total water treatment capacity of the MWA. Their respective service areas are shown in Fig. 2.

Recognizing the potentially critical situation, these major utilities, together with state and Federal governments, negotiated and signed a Low Flow Allocation Agreement (LFAA) thereby all utilities would share the Potomac River's water

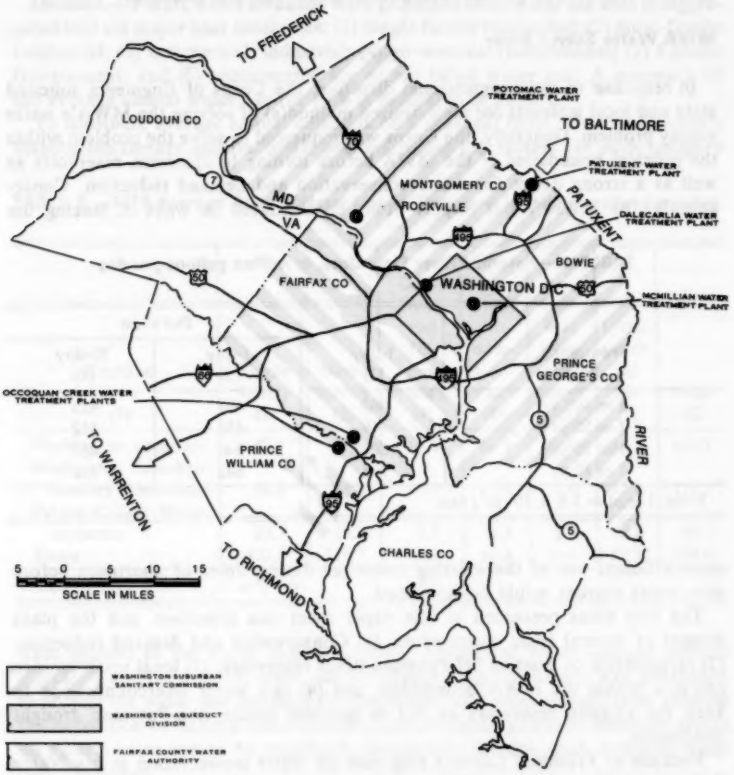

FIG. 2.—Major Water Supply Systems—Metropolitan Washington Area

during time of drought. The principle feature of the Agreement is a formula which limits the amount of water that may be withdrawn by each user during periods when Potomac River flow is insufficient to meet the total demands. In such an instance, each user would be allocated a percentage of the total available river flow based on a formula previously agreed to for dividing the flow. This agreement insures that the water resource is fairly distributed, but

it does not eliminate shortages. Other important features of the Agreement provide for: (1) A moderator to enforce the Agreement; (2) a definition of river flows and off-river reservoir storages subject to the Agreement; (3) a mechanism to inform users of different stages of river flow and their calculated fair share; and (4) a clause which allows any signatory to "freeze" the allocation formula ratios after 1988, pending the negotiation of a revised formula. The LFAA is, in essence, the first step taken in drought management by the region as a whole and not a piecemeal approach as the past has indicated.

MWA Water Supply Study

In response to the congressional directive, the Corps of Engineers solicited state and local interests for their desired method(s) of solving the MWA's water supply problem. Generally, the Corps was requested to solve the problem within the political boundaries of the MWA before turning to upstream reservoirs as well as a strong desire for water conservation and demand reduction. Consequently, the MWA Water Supply Study concentrated on ways of making the most efficient use of the existing resources during times of shortages before new water sources would be developed.

TABLE 1.—Potomac River Flow Data, in million gallons per day

Frequency (1)	Duration		
	1-day (2)	7-day (3)	30-day (4)
1 in 100 yr	369	401	423
1 in 50 yr	419	454	552
1 in 20 yr	505	546	654
1 in 10 yr	593	642	762

Note: 1 mgd = 3.8×10^3 m^3/day.

The five plans presented in this paper meet this objective, and the plans consist of several basic components: (1) Conservation and demand reduction; (2) reregulation of existing off-Potomac River reservoirs; (3) local small storage projects within the MWA boundaries; and (4) raw water interconnections to keep the existing reservoirs as full as possible during non-Potomac drought conditions.

Because of President Carter's emphasis on water conservation in his Water Policy guidelines of June 1978, special attention was devoted in the Corps' Study to water conservation and demand reduction measures as a starting point for any future alternative plans chosen for implementation.

Water Supply Problem

Supply.—Both statistical and historical flow simulation studies were made to determine how the Potomac River-dependent water users would experience shortages in relation to low flow recurrences and drought durations.

The annual series statistical frequency-duration data for the Potomac River near Washington, D.C., are presented in Table 1 for the years 1931–1976.

Correlating these data with historical flow data, it was found that the August 1930 monthly average flow closely approximated the once in 100 yr recurrence value for the 30-day flow duration and the 1966 7-day and 1-day flows closely approximated the once in 100 yr recurrence value for the 7-day and 1-day flow durations. Likewise, other historical events approximated the smaller recurrence levels.

Demand.—Future water demands were projected from water use data disaggregated into six major user categories: (1) Single family residential; (2) multi-family residential; (3) commerical/industrial; (4) government/institutional; (5) Federal Government; and (6) unaccounted for or not billed water use. A summary of the average annual water use for 1976 is presented in Table 2.

To distribute average annual demands on a seasonal basis, historical monthly distribution factors and fractional seasonal water use factors for each category

TABLE 2.—1976 Average Annual Water Use by Category, in million gallons per day

Demand area (1)	Single family (2)	Multi-family (3)	Commercial /industrial (4)	Government /institutional (5)	Federal government (6)	Unaccounted for (7)	Total (8)
Washington Aqueduct	42.5	63.4	16.6	10.9	27.6	34.2	195.2
Washington Suburban Sanitary Commission	61.6	38.0	17.9	3.6	5.0	13.0	139.1
Fairfax County Water Authority	28.7	15.3	7.3	3.7	3.8	4.9	63.7
Totals	132.8	116.7	41.8	18.2	36.4	52.1	398.0

Note: 1 mgd = 3.8×10^3 m^3/day.

were applied to the water demands. Then, having the water demand growth indicators and the monthly water use by category, a methodology was developed to project the water use demands for the future. This methodology later allowed the imposition of various water conservation scenarios and their resultant effect on future water use to be evaluated. Seven and one day peak demands were also developed.

Deficits.—Several assumptions were used to calculate the potential shortages given the information just presented. These assumptions were: (1) The Potomac Low Flow Allocation Agreement would remain in effect; (2) a 100 mgd (3.8×10^6 m^3/day) environmental instream flow need to the Potomac Estuary would be a constant demand (this value represents approximately the flow remaining in the river after all water supply withdrawals were made in 1966); (3) flow release from a Corps reservoir, Bloomington Lake, presently being constructed about 180 miles (290 km) upstream from the MWA would be 135 mgd (5.1

TABLE 3.—Calculated Deficits,

Frequency (1)	YEAR AND DURATION							
	1980			1990			2000	
	1-day (2)	7-day (3)	30-day (4)	1-day (5)	7-day (6)	30-day (7)	1-day (8)	7-day (9)
1/100	188	76	35	91	−30	−79	27	−100
1/50	243	124	69	150	23	−29	86	−47
1/20	345	216	155	252	115	57	188	45
1/10	453	312	243	360	211	145	296	141

Note: 1 mgd = 3.8×10^3 m^3/day.

$\times 10^6 m^3$/day) on a 30-day basis; and (4) use of 1-, 7-, and 30-day treatment plant capacities for the Occoquan [112 mgd (4.3×10^6 m^3/day), 95 mgd (3.6×10^6 m^3/day), 84 mgd (3.2×10^6 m^3/day)] and the Patuxent River [65 mgd (2.5×10^6 m^3/day), 55 mgd (2.1×10^6 m^3/day), 49 mgd (1.9×10^6 m^3/day)] water treatment plants.

Using the supply and demand data in conjunction with these assumptions, shortages for the four recurrence intervals and three durations were developed for the combined service areas. Table 3 presents the resultant deficits.

After determining the deficit levels for the range of durations and frequencies, the effects of a water shortage on each water user was ascertained. A hydrologic simulation of the 1930–1932 drought was performed using projected 2030 average monthly (30-day) demands for a once in 100 yr recurrence assuming that the local reservoirs were full and operating at their continuous safe yields. Fig. 3 graphically depicts the results. From this analysis, it was found that the Potomac River experienced low flow in the months of July 1930 through November 1930, while the Occoquan and Patuxent reservoirs emptied in February 1931 and December 1931, respectively.

Consequently, the following conclusion was reached: The water supply problem has two parts. Flow in the Potomac River could lead to shortages in those areas served by the Potomac River, even though there would be sufficient water in the off-stream reservoirs. The second aspect of the problem is the reverse; depleted storage could create a problem in the off-Potomac areas even with plentiful flow in the Potomac River. There is no way at present to manage these existing supplies with the river to better use the water in the area, and because of this, future shortages will occur in the MWA as well as locally. This finding was important, as it had a direct bearing on the analysis of ways to solve future water shortages and had been ignored in past water supply studies.

Design Condition

With many frequencies and durations to choose from and with the need to design plans capable and likely to be implemented, opinions were sought from advisory groups as to what design conditions would be the best to use. Essentially, the decisions were: (1) A 7-day drought duration; (2) a once in 100 yr drought

in million gallons per day

(+SURPLUSES, −DEFICITS)

2010				2020			2030		
30-day (10)	1-day (11)	7-day (12)	30-day (13)	1-day (14)	7-day (15)	30-day (16)	1-day (17)	7-day (18)	30-day (19)
−154	−27	−159	−217	−85	−223	−285	−135	−279	−346
−104	32	−106	−167	−26	−170	−235	−76	−226	−296
−18	134	−14	−81	76	78	−49	26	−134	−210
70	242	82	7	184	18	61	134	−38	−122

recurrence probability; (3) water conservation and demand reduction measures that would occur with the implementation of a 10% reduction in existing and projected demand with emergency or contingent drought plans to cover droughts of less than 7-day durations; (4) a 100 mgd flow-by ($3.8 \times 10^6 m^3$/day); and (5) a 135 mgd ($5.1 \times 10^6 m^3$/day) flow release from Bloomington Lake. Fig. 4 presents the aggregate deficits that would occur under the design condition which results in a 180 mgd ($6.8 \times 10^6 m^3$/day) maximum regional deficit by the year 2030. This regional water supply shortage was further analyzed to ascertain how much of the regional deficit would be experienced by each demand area. This was accomplished by first satisfying the individual demand area's needs with as much of their non-Potomac River supplies as possible and then attempting to satisfy the remainder with the Potomac River water. This division was accomplished by using the Potomac Low Flow Allocation Agreement formula. The service area deficits are given in Table 4.

Plans for Choice

During the final development of the plans, two questions evolved. First, what degree of regionalization and concomitant cooperation is appropriate? For instance, should each area provide in its programs a way for others to share in a project's benefits as well as its costs? Second, what implementation arrangements would be needed to attain the degree of cooperation required?

Also, the plans were evaluated according to several specific criteria: (1) Flexibility; (2) limited environmental impact; (3) ease of implementation; (4) economic equity; (5) low costs; (6) low risk; (7) planning compatibility; and (8) effects of social cohesion. Taking all things into consideration, the available combination of plans was reduced to five plans of choice. Table 5 presents these plans giving the date of operation and project size.

The "No Action Plan" presents the most probable water supply, demographic, economic, social, and environmental conditions likely to exist without any future water supply projects other than those already planned, e.g., Bloomington Lake, WSSC's expanded intake, FCWA's new intake, raising the Occoquan Dam 2 ft, 100 mgd (3.8×10^6 m^3/day) flow-by, existing conservation plans, and the LFAA.

The "Local Plan" has each supplier meeting its own water needs with individual

projects. Regional cooperation is still required for successful implementation; however, the individual projects are operated more from a single viewpoint rather than from a collective viewpoint.

The "Subregional Plan" is indicative of two subregional arrangements, because the Little Seneca Lake costs would be shared by WSSC and WAD, and the

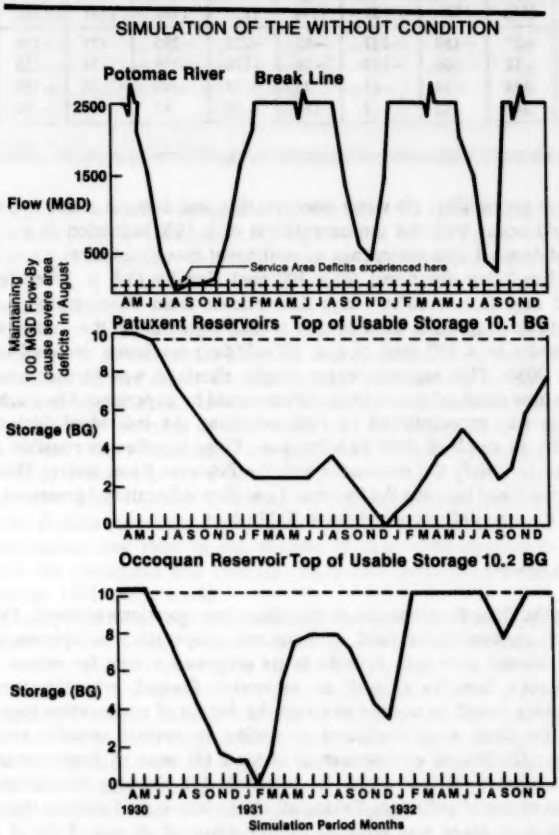
SIMULATION OF THE WITHOUT CONDITION
Potomac River
Break Line
2500
1500
Flow (MGD)
500
Service Area Deficits experienced here
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Maintaining 100 MGD Flow-By cause severe area deficits in August
Patuxent Reservoirs Top of Usable Storage 10.1 BG
10
8
6
Storage (BG)
4
2
0
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Occoquan Reservoir Top of Usable Storage 10.2 BG
10
8
6
Storage (BG)
4
2
0
A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1930
1931
1932
Simulation Period Months

FIG. 3.—Simulation of Without Condition (1 mgd = 3.8×10^3 m^3/day)

raw water interconnection costs would be shared by FCWA and WAD. A greater degree of regional cooperation is necessary for the successful implementation of this plan when compared to the local plan.

The "Regional Plans" are regionally based because the projects' costs are equally shared by the major Potomac River users collectively, and total regional

cooperation is necessary for these schemes to physically work.

Several factors played an important role in the development of engineering data and cost-sharing data. Important to the development of component capacities

TABLE 4.—7-Day Deficits by Service Areas, in million gallons per day

Time period (1)	SERVICE AREA					
	WSSC		FCWA		WAD	
	1988 allocation (2)	2030 allocation (3)	1988 allocation (4)	2030 allocation (5)	1988 allocation (6)	2030 allocation (7)
1980	+35	+35	+14	+14	+56	+55
1990	+2	+8	0	0	+20	+14
2000	−15	−13	−13	−9	0	−6
2010	−48	−34	−29	−13	0	−24
2020	−80	−57	−52	−33	0	−42
2030	−106	−77	−72	−46	−2	−57

Note: 1 mgd = 3.8×10^3 m^3/day.

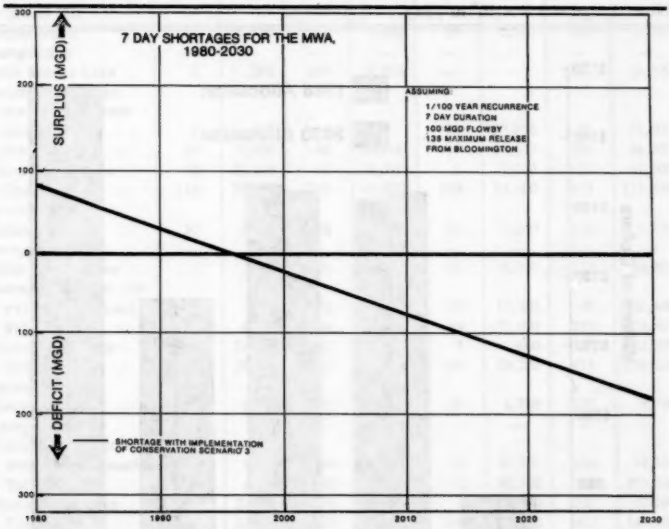

FIG. 4.—7-Day Shortages for MWA, 1980–2030 (1 mgd = 3.8×10^3 m^3/day)

and resultant costs was the effect of the Potomac Low Flow Allocation Agreement on the water service areas. Depending upon which formula is used, i.e., 1988 "freeze" or "rolling" average, different water shortages result.

TABLE 5.—Plans for Choice

Component (1)	Plans				
	1 (No action) (2)	2 (Local plan) (3)	3 (Sub-regional plan) (4)	4 (Regional plan) (5)	5 (Regional plan) (6)
Conservation		1980–2030	1980–2030	1980–2030	1980–2030
Reregulation by FCWA and WSSC		1980	1980	1980	1980
Bloomington Lake	1981 (135 mgd)	1981 (135 mgd)	1981 (135 mgd)	1981 (135 mgd)	1981 (135 mgd)
Little Seneca Lake		1995 (114 mgd)	1994 (120 mgd)	1994 (120 mgd)	
Potomac/Patuxent: raw water interconnection				2017 (60 mgd)	1994 (180 mgd)
Potomac/Occoquan: raw water interconnection		1990 (72 mgd)	1994 (74 mgd)		

Note: 1 mgd = 3.8×10^6 m^3/day.

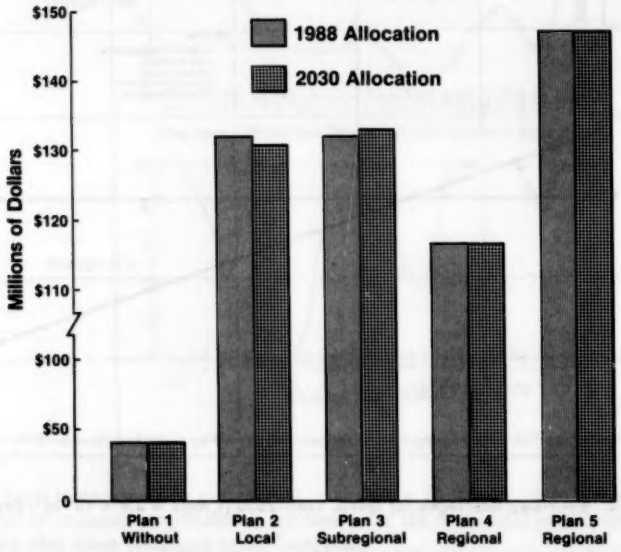

FIG. 5.—Comparison of Plan Costs

TABLE 6.—1988 Allocation Ratio: Construction Costs Apportionment

Plan (1)	Washington Aqueduct and Rockville[a]		WSSC		FCWA		Total[c]	
	Project size, in million gallons per day (2)	Cost, in December 1978 dollars (3)	Project size, in million gallons per day (4)	Cost, in December 1978 dollars (5)	Project size, in million gallons per day (6)	Cost, in December 1978 dollars (7)	Project size, in million gallons per day (8)	Cost, in December 1978 dollars (9)
Without plan								
Bloomington Lake[b]	73	23,400	57	18,300	5	1,600	135	43,300
Local plan								
Conservation	35	3,900	42	3,600	23	2,200	100	9,700
Reregulation	—	—	—	—	—	—	—	—
Little Seneca Lake	—	—	108	20,200	—	—	108	20,200
Potomac-Occoquan: raw water interconnection	—	—	—	—	72	58,600	72	58,600
Subtotal	35	3,900	150	23,800	95	60,800	280	88,500
Bloomington Lake	75	24,100	55	17,600	5	1,600	135	43,300
Total	110	28,000	205	41,400	100	62,400	415	131,800
Subregional plan								
Conservation	35	3,900	42	3,600	23	2,200	100	9,700
Reregulation	—	—	—	—	—	—	—	—
Little Seneca Lake	1	200	106	20,000	—	—	107	20,200
Potomac-Occoquan: raw water interconnection	1	800	—	—	72	57,800	73	58,600
Subtotal	37	4,900	148	23,600	95	60,000	280	88,500
Bloomington Lake	73	23,400	57	18,300	5	1,600	135	43,300
Total	110	28,300	205	41,900	100	61,600	415	131,800
Regional plan								
Conservation	35	3,900	42	3,600	23	2,200	100	9,700
Reregulation	—	—	—	—	—	—	—	—
Little Seneca Lake	1	200	71	12,000	48	8,000	120	20,200
Potomac-Patuxent: raw water interconnection	1	700	35	25,300	24	17,400	60	43,400
Subtotal	37	4,800	148	40,900	95	27,600	280	73,300
Bloomington Lake	73	23,400	57	18,300	5	1,600	135	43,300
Total	110	28,200	205	59,200	100	29,200	415	116,600
Regional plan								
Conservation	35	3,900	42	3,600	23	2,200	100	9,700
Reregulation	—	—	—	—	—	—	—	—
Potomac-Patuxent: raw water interconnection	2	1,000	106	55,400	72	37,700	180	94,100
Subtotal	37	4,900	148	59,000	95	39,900	280	103,800
Bloomington Lake	73	23,400	57	18,300	5	1,600	135	43,300
Total	110	28,300	205	77,300	100	41,500	415	147,100

[a] Rockville comprises approximately 2% of the combined costs and flows of the Washington Aqueduct and Rockville Service Areas.

[b] Represents cost of remaining water supply storage not yet contracted. All Bloomington Lake projects costs are based on 3-1/4% interest rate as authorized.

[c] Numbers may not total due to rounding.

Note: 1 mgd = 3.8×10^3 m^3/day.

TABLE 7.—2030 Allocation Ratio: Construction Costs Apportionment

Plan (1)	Washington Aqueduct and Rockville[a]		WSSC		FCWA		Total[c]	
	Project size, in million gallons per day (2)	Cost, in December 1978 dollars (3)	Project size, in million gallons per day (4)	Cost, in December 1978 dollars (5)	Project size, in million gallons per day (6)	Cost, in December 1978 dollars (7)	Project size, in million gallons per day (8)	Cost, in December 1978 dollars (9)
Without plan								
Bloomington Lake	49	15,700	56	18,000	30	9,600	135	43,300
Local plan								
Conservation	35	3,900	42	3,600	23	2,200	100	9,700
Reregulation	—	—	—	—	—	—	—	—
Little Seneca Lake	—	—	114	20,200	—	—	114	20,200
Potomac-Occoquan: raw water interconnection	—	—	—	—	66	58,400	66	58,400
Subtotal	35	3,900	156	23,800	89	60,600	280	88,300
Bloomington Lake	106	34,000	19	6,100	10	3,200	135	43,300
Total	141	37,900	175	29,900	99	63,800	415	131,600
Subregional plan								
Conservation	35	3,900	42	3,600	23	2,200	100	9,700
Reregulation	—	—	—	—	—	—	—	—
Little Seneca Lake	28.5	5,500	77	14,700	—	—	105.5	20,200
Potomac-Occoquan: raw water interconnection	28.5	22,500	—	—	46	36,200	74.5	58,700
Subtotal	92.0	31,900	119	18,300	69	38,400	280.0	88,600
Bloomington Lake	49	15,700	56	18,000	30	9,600	135	43,300
Total	141	47,600	175	36,300	99	48,000	415	131,900
Regional plan								
Conservation	35	3,900	42	3,600	23	2,200	100	9,700
Reregulation	—	—	—	—	—	—	—	—
Little Seneca Lake	38	6,400	51	8,600	31	5,200	120	20,200
Potomac-Patuxent: raw water interconnection	19	13,700	26	18,800	15	10,900	60	43,400
Subtotal	92	24,000	119	31,000	69	18,300	280	73,300
Bloomington Lake	49	15,700	56	18,000		9,600	135	43,300
Total	141	39,700	175	49,000		27,900	415	116,600
Regional plan								
Conservation	35	3,900	42	3,600	23	2,200	100	9,700
Reregulation	—	—	—	—	—	—	—	—
Potomac-Patuxent: raw water interconnection	57	29,800	77	40,300	46	24,000	180	94,100
Subtotal	92	33,700	119	43,900	69	26,200	280	103,800
Bloomington Lake	49	15,700	56	18,000	30	9,600	135	43,300
Total	141	49,400	175	61,900	99	35,800	415	147,100

[a] Rockville comprises approximately 2% of the combined costs and flows of the Washington Aqueduct and Rockville Service Areas.

[b] Represents cost of remaining water supply storage not yet contracted. All Bloomington Lake projects costs are based on 3-1/4% interest rate as authorized.

[c] Numbers may not total due to rounding.

Note: 1 mgd = 3.8×10^3 m^3/day.

The plan components and their associated costs are presented in Table 6 for the 1988 allocation ratio, while Table 7 presents costs for the 2030 allocations. Costs of reservoir reregulation were assumed to be minimal and are not reflected in the plans' costs. The costs shown for Bloomington Lake represent only the portion of the Bloomington Lake water supply storage not yet contracted. Conservation Scenario 3 costs are based on the cost of various procedures and devices used to achieve an approximate 10% reduction in demand by the year 2030. Additionally, the cost associated with the Occoquan interconnection varies slightly to account for different pump station capacities required to accommodate different flows.

The cost apportionments presented in Tables 6 and 7 present the costs of

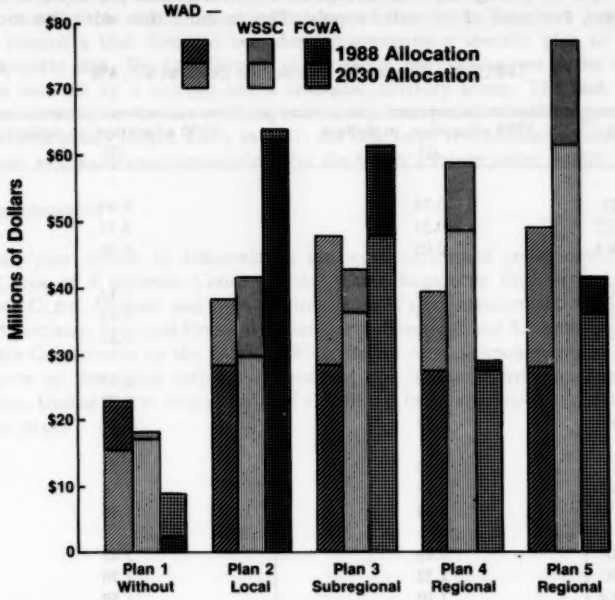

FIG. 6.—Comparison of Service Area Costs

the plan component each user shares in that component according to the extent that the user benefits from that specific component.

Fig. 5 graphically presents the construction costs of the plans while Fig. 6 gives a comparison of the service area costs.

The 1988 allocation favors WAD at the expense of WSSC and FCWA. Plan 4 would be the most cost-effective plan from a regional standpoint; however, this is not true for every service area, notably the WSSC. From WSSC's viewpoint, Plans 2 and 3 would be more cost effective. This is quite evident when the cost of the plans is reduced to an annual per capita plan cost using an interest rate of 6-7/8% as shown in Table 8.

Regional cooperation in times of a drought will be crucial to effectively implement any of these plans. Varying degrees of cooperation have been presented among the five plans. However, to realize the greatest return or to achieve the greatest cost effectiveness also requires a greater degree of cooperation among the water service areas.

Summary

The Metropolitan Washington Area generally depends on the Potomac River, which has an average flow of more than a billion gallons per day (3.8×10^6 m^3/day), for most of its water supply. This is more than adequate to meet

TABLE 8.—Annual Per Capita Plan Costs at 6-7/8%

Plan (1)	1988 allocation, in dollars (2)	2030 allocation, in dollars (3)
Plan 1		
WAD	0.74	0.49
WSSC	0.31	0.31
FCWA	0.05	0.26
Plan 2		
WAD	0.85	1.16
WSSC	1.05	0.85
FCWA	3.21	3.25
Plan 3		
WAD	0.89	2.32
WSSC	1.05	0.87
FCWA	3.18	2.24
Plan 4		
WAD	0.88	1.82
WSSC	1.59	1.26
FCWA	1.44	1.16
Plan 5		
WAD	0.89	2.43
WSSC	2.22	1.70
FCWA	2.10	1.59

projected regional demands. Because the Potomac River is essentially unregulated, in periods of drought this supply falls well below this average and, in 1966, the river reached a record low of 388 mgd (1.5×10^6 m^3/day). In addition, localized shortages within off-Potomac service areas have also demonstrated a potentially serious problem—the MWA has and will probably face severe water shortages in the future.

To solve this short-term problem, the Corps of Engineers released a progress report which outlines plans for choice which draw upon: (1) Water conservation and demand reduction; (2) reregulation of existing reservoir systems; (3) constructing a local storage reservoir; and (4) constructing a raw water interconnection pipeline between the Potomac River and an off-Potomac River water supply

source. These plans are designed to meet the 7-day, once in 100 yr drought situation and rely upon contingency conservation measures to help the MWA cope with less than 7-day droughts.

Based on the data presented, the 1988 allocation favors the Washington Aqueduct, while the 2030 allocation favors the Washington Suburban Sanitary Commission and the Fairfax County Water Authority. While Plan 2 represents a higher cost alternative, it also requires the least amount of cooperation among the utilities because each would implement projects for their individual needs. To achieve the greatest cost effectiveness, Plan 4 involves the greatest need for regional cooperation.

As a result of the Corps' report, it was agreed by all parties that some positive action needs to be taken to implement any of the plans. The three suppliers have formed a task force to consider implementing a specific plan or parts of a specific plan. The task force is composed of political leaders in the MWA and is assisted by a citizens and a technical advisory group. The task force is concentrating on factors such as economics, interjurisdictional cooperation, and overall policy issues. Early in 1981, the task force is scheduled to complete its work and make recommendations for the MWA's future water wealth.

Acknowledgments

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JOURNAL OF THE WATER RESOURCES PLANNING AND MANAGEMENT DIVISION

COMPUTER MODEL FOR SMALL-SCALE HYDROPOWER POLICY ANALYSIS

By Paul H. Kirshen,[1] A. M. ASCE
and Jeffrey S. Amlin[2]

INTRODUCTION

As part of a study to identify the legal, economic, and institutional obstacles to and incentives of small-scale hydropower development, and to recommend to the United States Department of Energy (DOE) policies that will encourage the development of small-scale hydropower, a computer simulation model of several of the major factors that encourage or discourage small-scale hydropower development was designed and implemented in the period 1978–1979. It is called HYDRO-I and is described in detail in Ref. 1. HYDRO-I uses a technique called "system dynamics," and its associated computer language DYNAMO (see Refs. 4 and 6). Similar techniques have been used to study such diverse policy issues as cattle grazing strategy (12), national energy policy (11), river basin development (7), and heroin addiction (10); these studies all used systems characterized by feedback. The small-scale hydropower (SSH) model is intended to help analysts and policymakers understand the far-reaching implications of their policy recommendations by simulating the interrelationships of the factors modeled. While the model cannot be expected to mkae precise quantitative predictions, it does provide insight on the pertinent consequences of policy recommendations.

This paper describes HYDRO-I and the modeling techniques employed in its construction, and examines the model's value for policy analysis. Some preliminary policy analysis is also presented.

[1]Asst. Prof., Dept. of Civ. Engrg., Virginia Polytechnic Inst. and State Univ., Blacksburg, Va. 24061.
[2]Research Scientist, Battelle Columbus Labs., Columbus, Ohio 43201.

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Usefulness of System Dynamics Modeling.—A computer model resembles, in many ways, the mental process any person uses to direct actions toward a certain goal. Both the mental process and the computer model use a great variety of facts, theories, and educated guesses to try to account for all the actions that have caused or will sustain a certain desirable or undesirable course of events. The computer model tends to be more precise and explicit than the mental model. Unlike most mental models, it is comprehensive and unambiguous, and can be subjected to rigorous logical experimentation. Analysts do not claim that computer models offer perfectly accurate representations of reality or make better decisions than people can. However, such models have been proven to be very useful in amplifying the efficiency of the human mental process by identifying important omissions, inconsistencies, or errors in understanding (see Refs. 5 and 10).

Computer models are also extremely useful because they can be easily modified or updated to account for new information and conditions. This is important in the field of SSH as better data are constantly becoming available and new regulations being issued.

Construction of HYDRO-I.—Hydropower development can be seen as the interaction of six factors or sectors: economic, licensing, equipment, construction, retirement, and environmental and social. The interrelations of these sectors are shown in Fig. 1. As an initial model of the dynamics of small-scale hydropower development, HYDRO-I includes only four of the sectors, i.e., economics, licensing, construction, and retirement. These sectors were chosen because the most data were available for them. The other sectors will be added in a later model as more research is completed. HYDRO-I includes only sites already in existence in New England with a maximum potential of 15 MW. (At the start of the research, this was the common definition of SSH. It is now generally 25 MW.) It is assumed that the owners of the sites will be paid the replacement cost of electricity for the power generated, and that all sites under consideration will be operated independently of each other. It is also assumed all dams have the same capacity factors (defined as the ratio of the average annual generation and the theoretical maximum annual generation), and the same installed capacities.

In any one analysis with the model, it is assumed that all SSH development is done by one type of developer: an investor-owned utility (IOU), an entrepreneur, a municipality, or a private company generating power for use on-site. Different borrowing rates, tax lives, financial lifetimes, debt/equity ratios, and returns, are used in each analysis with the model to reflect the different points of view of these developers. Adjustment can be made outside of the model to account for the actual situation of many types of developers simultaneously developing sites.

In the process of system dynamics modeling, diagrams and mathematical equations are used to make a progressively more comprehensive and precise statement of theories about causes and influences in a complex system. The key concepts are identified and the connecting causal relationships are noted in causal loop diagrams. The conventions of causal loop diagramming are explained in detail in numerous system dynamics tests (e.g., see Ref. 6). The diagram is a convenient way to summarize diverse quantities of practical experience, empirical data, and intuitive judgment.

Shown in Fig. 2 is the causal loop diagram (CLO) for HYDRO-I. The effect

of one factor on another is shown by an arrow and sign at the end of the arrow. If the sign is positive, (+), it means that if one factor increases, the other increases. A negative sign (−) means that if one factor increases, the other factor decreases. An example of positive causality is that if licensing requirements increase, licensing delays increase; similarly if licensing requirements decrease, licensing delays decrease. An example of negative causality is if the permit delay time decreases, the permit issuance rate increases. The CLD also summarizes the major data requirements of the model. Generally, the exogenous variables (those only with arrows leading from them in the CLD) require input data values (either constants or time-varying) for the entire simulation period. The values of the endogenous variables are calculated internally in the model once normalized or initial values are given by the user. The diagram and the sectors of the model are examined in detail in the following.

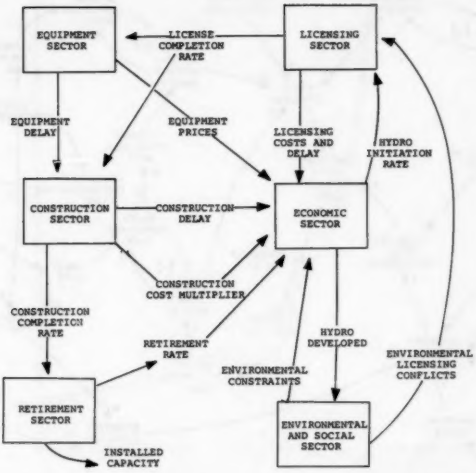

FIG. 1.—Small-Scale Hydropower Sectorial Boundary Diagram (1)

The process in HYDRO-I commences when a developer decides to study the feasibility of a site based on its projected fuel-saver and capacity credit values when the plant starts operation. This is termed "project initiation" and takes place in the economic sector of the model. The project then goes through the licensing, construction, and retirement sectors. After a project has been retired, it is eligible again for rehabilitation or replacement. The model calculates the status of each of these sectors every 0.10 yr. Results are printed or plotted for each year.

Economic Sector.—The essence of the economic sector is the supply curve shown in Fig. 3. SSH development is assumed to be initiated in any time period whenever the value of hydropower increases over its past value. As shown in the figure, the increment of hydrocapacity corresponding to the increased

value is the amount initiated in that time period. The value of the power is the projected value based on capacity credit and fuel-saver value. The capacity credit is based on the assumed mix of generation that the hydropower will replace (coal-fired base, oil-fired intermediate, and peak), and the reliability attributed to the hydropower. (The reliability is approximated by the plant's

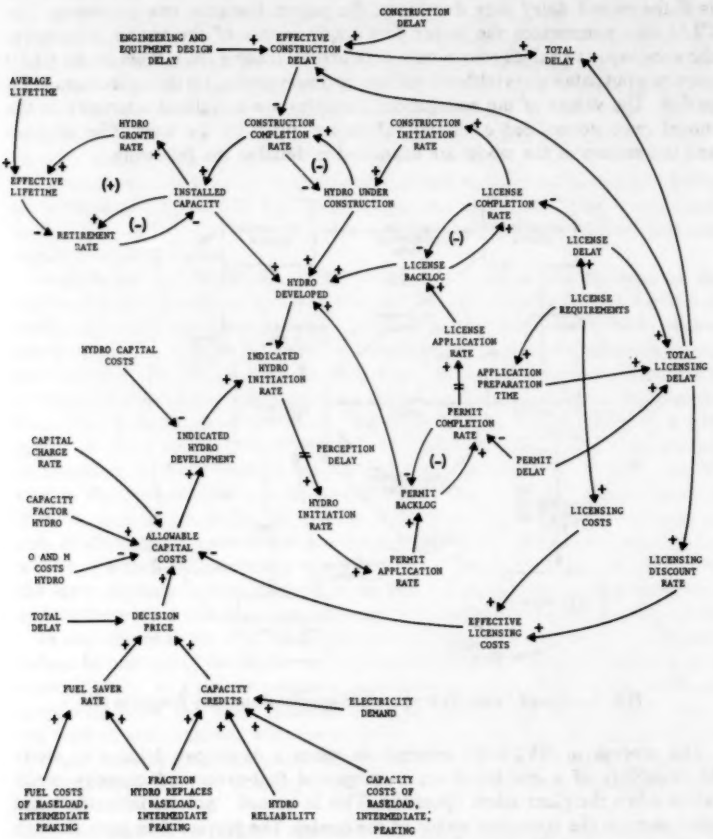

FIG. 2.—Causal Loop Diagram for Small-Scale Hydropower (1)

capacity factor.) The developer is uncertain of the fuel-saver value he will receive, and therefore bases his projections of the value on the previous rate of growth of fuel costs (the fuel cost estimates are those of the Electric Power Research Institute as given in Ref. 2. The fuel-saver costs are based on the assumed mix of generation replaced by the hydropower. In the model, all costs

and benefits are compounded or discounted to the expected time of start of operation. Therefore, the uncertainty in the projections of fuel costs is modeled so that as the difference between the present value of the electricity and the projected value grows, the discount rate on the power revenues also increases, and vice versa. The increase in the discount factor ranges from no increase to an increase 2.0 times the original.

A developer also faces uncertainty in obtaining a plant license. Therefore, the compound factor for the licensing costs, which includes the feasibility study and legal costs, increases as the licensing delays and requirements increase. The increase may be as much as tenfold.

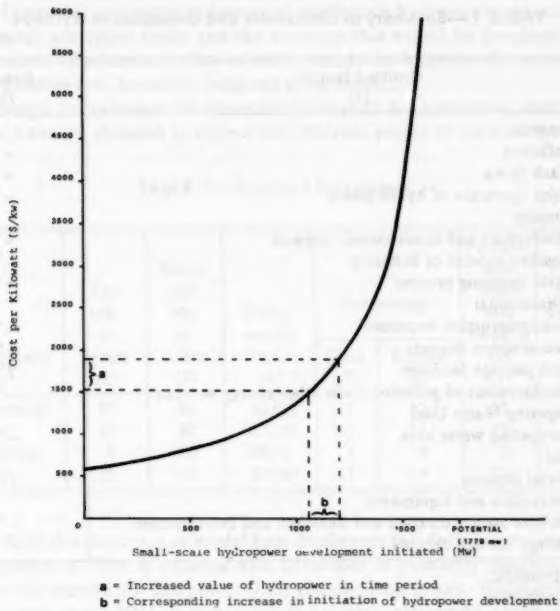

FIG. 3.—Cost Versus Small-Scale Hydropower Development Initiated (58% capacity factor) (9)

All costs are in constant 1978 dollars. The costs of the feasibility study, licensing, construction and interest, land purchase, transmission, operation and maintenance, taxes, and insurance are included. Sensitivity analysis is done to assess the effects of uncertain values.

Licensing Sector.—It is assumed that all projects receive both preliminary permits and licenses. Only under extreme conditions will an environmental impact statement be required for existing small-scale hydropower sites; this requirement is therefore omitted from this sector. As there are no competing water uses or other prohibitive environmental or social factors included in HYDRO-I, all

projects in the model are eventually licensed.

Initiated projects are subjected to permitting and licensing delays. The delays are functions of the availability and productivity of staff at the Federal Energy Regulatory Commission (FERC) and licensing requirements (e.g., need for outside review, required exhibits, hearings, etc.). Licensing costs vary with licensing requirements.

Construction Sector.—Once a project has been licensed, it enters the construction sector. The time taken for construction is based on an average construction period of 2 yr and the number of small-scale hydroplants already under construction.

TABLE 1.—Summary of Limitations and Omissions in HYDRO-I

Omitted factors (1)	Results (2)
Economic	
Inflation	+[a]
Cash flows	+[a]
Joint operation of hydro plants	−[b]
Licensing	
Intervenors and noneconomic impacts	+[a]
Positive aspects of licensing	−[b]
State licensing process	+[a]
Environmental	
Nonconstruction impacts	+[a]
Construction impacts	+[a]
Fish passage facilities	?[c]
Displacement of pollution from other energy sources	−[b]
Competing Water Uses	
Competing water uses	+[a]
Social	
Social impacts	?[c]
Construction and Equipment	
Turbine standardization and Research and Development	−[b]
Energy storage devices	−[b]

[a] + = Optimistic.
[b] − = Pessimistic.
[c] ? = Questionable.

Retirement Sector.—The number of plants retired per year is based on the average lifetime of hydropower plants. The model assumes that the average lifetime of plant and equipment will increase as the small-scale hydroindustry grows.

Evaluation of HYDRO-I

Before a mathematical model can be effectively used in the policy process it must be carefully evaluated for its limitations and biases so that these can be considered in the interpretation of results. The evaluation procedure of

HYDRO-I consisted of reviewing the model's omissions, determining how well its results reflected past known development trends, and testing the sensitivity of the results to poor quality data and major assumptions.

Limitations.—The limitations and omissions of HYDRO-I are listed in Table 1 and explored in detail in Ref. 9. These limitations and omissions affect the results of the model in either an optimistic (i.e., the model predicts more development than will actually occur) or pessimistic manner.

In a preliminary model such as HYDRO-I, limitations and omissions arise because of an absence of data, and an emphasis on modeling the essential elements of the hydropower development process. An examination of the table and an estimation of the relative weights of the effects indicate that, overall, HYDRO-I provides optimistic estimates of small-scale hydropower development. The estimates are upper limits and the amounts that would be developed under "best possible conditions." The relative trends in hydrodevelopment under different policies are, however, believed to be correct.

Even though the values of the financial parameters (interest rates, debt/equity ratios, etc.) can be changed to reflect the different points of view of the several

TABLE 2.—Financial Parameters

Development (1)	Tax life, in years (2)	Financial life, in years (3)	Debt/equity ratio (4)	Percentage Return		Percentage state and Federal tax (7)	Percentage investment tax credit (8)
				Debt (5)	Equity (6)		
Entrepreneur	35	30	80/20	11	40	52	7
IOU	40	30	65/35	11	13	52	7
Municipality	0	30	100/0	7	0	0	0
Industry	35	10	20/80	11	13	52	7

types of SSH developers, the model best duplicates the decision-making criteria of entrepreneurs. This is because this developer is primarily interested in the value he will receive for his power (i.e., the decision price). While other types of developers (e.g., IOU, municipalities) are also concerned about this, they have other important concerns that are not modeled. Examples of these include: regulated rates of return on capital for IOU, the need for public approval of expenditures by municipalities, and the need for backup power by industrial self-suppliers. Thus, due to these omissions, the entrepreneurial point of view is best modeled in HYDRO-I.

The next step in the model's evaluation is to examine how well the results reflect past known development trends.

Historical Comparison.—Using the financial parameters for entrepreneurs (see Table 2), and data on the installed capacity of small-scale hydropower, and the estimated development costs, and the value of small hydropower in 1960, hydrodevelopment was simulated from 1960–2000. As can be seen in Fig. 4, there was a decrease in installed capacity from approx 670 MW in 1960 to

620 MW in 1975. (This analysis or run is hereafter referred to as the reference run or base case.) Analyses using data representative of the three other types of developers (see Table 2) also show the same trends. These results indicate that hydrodevelopment has been unfavorable from all points of view in this period and retirements have exceeded additions of new capacity. These results agree well with historical data from the Federal Power Commission (3). Thus, the model is realistic.

Explanation of Graph of Model Output.—The horizontal scale of Fig. 4 shows the time period of interest (1960–2000). Several variables are plotted in each graph so that comparisons can easily be made. The values of the parameters are given on the vertical scale with the range of values corresponding to a particular variable identified by that variable being placed above it. For example, the outer range of Fig. 4(*b*) (0–1600), corresponds to the variable, C, the cumulative installed capacity of hydropower.

The other variables plotted are the following: I = the amount of development initiated in 1 yr (in megawatts); D = the price a developer plans on receiving for hydropower once it comes on line (in millions per kilowatt hours); A = the actual value of hydropower, given present fuel costs and capacity credits (in millions per kilowatt hours); and H = the cost to develop a plant (in millions per kilowatt hours).

This particular graph shows the initiation of development when the decision price, D, exceeds the cost of development, H, around 1977. Due to feasibility, licensing, and construction delays, installed capacity, C, starts to increase approx 6 yr later. Installed capacity had been decreasing up to this time because of the retirement of plants.

Parameter Sensitivity.—The testing of the individual effects of variables with poor quality data indicated that the model results are sensitive mainly to the time delay between increases in fuel prices and corresponding increases in the value of electricity. This is expected because fuel prices account for the greatest costs in producing electricity from fossil fuel plants. When considered in interaction and combination with other time delays (e.g., licensing and construction), the sensitivity of the model to this parameter is not, in actual fact, severe. Doubling the delay in the model results in a decrease of only 30% in the amount of hydropower developed between 1980 and 2000 and a tenfold decrease in delay results in no appreciable increase in development. These poorly documented variables were further tested by setting them all at the values that simulated development the most and then the least. The former resulted in no appreciable differences in the increase between 1980 and 2000, but caused different development rates. The latter caused slower development rates and only a 30% decrease in net development. The results of the testing were consistent with perceptions of how the model should react to these changes. Thus, this suggests that there are no unknown, contradictory sections in the model. The overall conclusion from this testing is that using estimates for these variables is justified as the model is relatively insensitive to them.

Assumptions in Model.—Several assumptions were tested to see whether they had detrimental effects on the results. The first assumption examined was that the size of each hydroplant was 2 MW. Because of economies of scale and the resulting changes in unit costs, it was found that larger average sizes caused development to start earlier and smaller average sizes caused development to

start later. Therefore, the results of HYDRO-I need to be adjusted for the size distribution in New England. For example, if in reality large sites are developed before small sites, then the rates and quantity of development displayed by the model in the later years are too optimistic.

It is also assumed in the model that the capacity factors of all plants are the same (58% the average value over the period 1960–1976, as documented

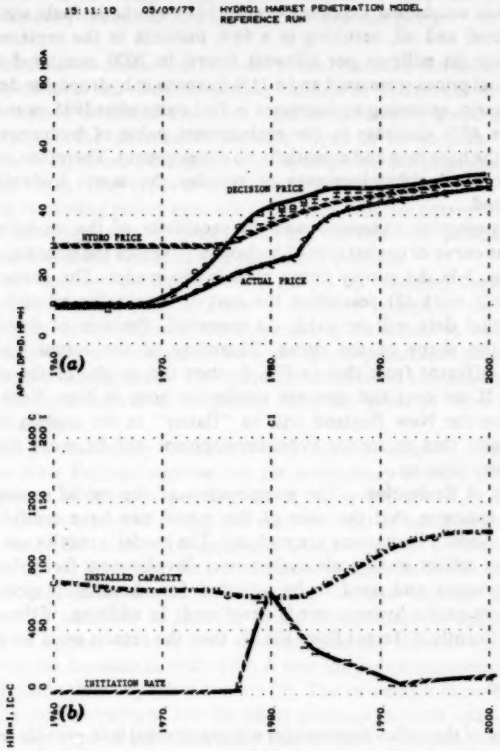

FIG. 4.—Simulation of SSH Development: (*a*) Financial Information; and (*b*) Initiation Rate and Cumulative Installed Capacity (1)

in Ref. 3). Changes in the capacity factor affect the economic return of a plant because of the amount of energy produced and the reliability factor used in the model for determining capacity credits. Changing the capacity factor also changes the potential capacity available in the region. The estimated potential at 58% is 1,780 MW. Analyses were made at 40% (potential of 2,550 MW) and at 70% (potential of 1,520 MW). As was expected, at the lower capacity factor the initiation of hydropower was delayed in comparison to the 58% capacity

factor case, and the quantity of hydropower developed and the economically feasible hydrodevelopment cost in the year 2000 were both less. At 70% capacity factor, the reverse occurred, though the differences were not as great. The results of HYDRO-I must therefore be adjusted for this discrepancy. For example, if in reality higher capacity factor plants are developed first, then the rate of development will be greater than displayed by the model.

Another assumption examined was the projected rate of increase in fuel cost. A test run was conducted assuming that in 1985 synthetic fuels would be used in place of coal and oil, resulting in a 66% increase in the replacement value of hydropower (in millions per kilowatt hours) in 2000 compared to the case when fossil fuel prices were used and a 25% increase in hydropower development. Another scenario, assuming no increases in fuel costs after 1985, was also tested, resulting in a 45% decrease in the replacement value of hydropower in 2000 compared to the base case and essentially no development. Therefore, as expected, if the cost of fuel either increases or remains the same, hydrodevelopment will be affected.

The last assumption examined was the sensitivity of the model's results to the exogenous curve of capital cost of hydropower versus the quantity developed. Shown in Fig. 3 is the supply curve used in the model. The curve is derived from Hubbert's work (8) describing the cost of developing oil and gas. When available, actual data will be used. As expected, the rate of development is sensitive to the shape of the curve. Therefore, if the actual cost curve is significantly different from that in Fig. 3, then the results of the model must be adjusted. If the cost and size are similar to those in New York (13), then the cost curve for New England will be "flatter" in the middle than in Fig. 3. This suggests that in reality hydrodevelopment will be more rapid at first and then slower later on.

Conclusions of Evaluation.—The examination of the model's omissions and assumptions indicates that the user of the model can have confidence in its results if the model's limitations are realized. The model's results are optimistic. They also best reflect small-scale hydropower development from the viewpoint of the entrepreneur and need to be adjusted for changing project sizes and capacity factors as the hydropower is developed. In addition, if the actual cost curve is significantly different from Fig. 3, then the results must be adjusted.

Policy Analysis

The purpose of the policy analyses (or computer runs) is to provide assessments of the impacts of some policies that could be pursued to stimulate the development of hydropower. All the policy runs are compared to the "reference run," i.e., to development by entrepreneurs assuming that there are no new policies implemented to aid small-scale hydrodevelopment. The reference run was shown in Fig. 4. The parameters are compared for the years 1990 and 2000 and are given in Table 3. They are:

1. The number of years between hydro-initiation in the policy run and initiation in the reference run.
2. The ratio of installed capacity in the policy run to that in the reference run (*IC*).

3. The ratio of the projected captial cost of economically feasible hydropower to that in the reference run (based on the decision price explained in the following) (*ICCH*).

4. The ratio of the actual value of hydropower in the policy run to that in the reference run (*AP*).

5. The ratio of the projected value of hydropower (or the decision price) when it comes on line (approx 6 yr after initiation) based on projected fuel prices and capacity credits to that in the reference run (*DP*).

Entrepreneur development was chosen for the reference run because the model most clearly reflects the decision-making criteria of entrepreneurs. The results can be expected to be similar for other types of developers given the limitations of the model and the differences between types of developers. The first set of policy runs is therefore a comparison of hydropower development as estimated by the model for the four types of decision makers. The differences are analyzed and then the remaining policy runs are conducted only for entrepreneur development. The remaining sets of policy runs are on financial policies, regulatory policies, and combined financial and regulatory policies.

Differences between developers are modeled by changing the values of the financial parameters, shown in Table 2. Table 3 compares the policy runs. Considerably more hydropower development is estimated to occur when the financial parameters established for IOU and municipalities are used. In addition, development is initiated earlier. This indicates the relative economic attractiveness of small-scale hydropower development from the point of view of these two types of developers.

This result is reasonably consistent with what is actually occurring. Table 4 shows the New England applications for preliminary permits and for licenses or amendments to licenses pending as of April 14, 1979. As can be seen, municipalities are clearly showing the most interest in small-scale hydropower both in terms of the number of applications and capacity. A further conclusion that can be drawn from the data in Table 4 is that, in terms of the number of applications, entrepreneurs are showing definite interest in small-scale hydropower. In addition, at least in terms of numbers of applications, IOU and industries appear to have less interest than the others. This is expected for the industries because in 1960–1976 it was the industrial owners who retired more small plants than any other owners (3). The two major factors discouraging industrial hydrodevelopment are the short payback periods required on major projects by this type of developer and the necessity for purchasing expensive peak or backup power to supplement their own hydroelectric power.

The IOU apparent lack of interest in the development of small-scale hydropower may be the result of certain institutional or economic factors unique to New England. New York State utilities are actively developing small hydropower dams (13). This finding requires further research.

Financial Policy Runs.—The effects of several financial policies on entrepreneur development are shown in Table 3. Development is slowed if entrepreneurs make decisions based on the current value of hydropower rather than on a forecasted value and if they are not given capacity credits by the public utilities. Such may be the case if the power purchasers are not willing to guarantee increases in the price paid for the power as fuel costs rise and system capacity

TABLE 3.—Results of Policy Runs Compared to Reference Run

Policy Run (1)	Start of initiation compared to reference run (2)	1990				2000			
		IC (3)	*ICCH* (4)	*AP* (5)	*DP* (6)	*IC* (7)	*ICCH* (8)	*AP* (9)	*DP* (10)
Types of developers									
Entrepreneur (reference run)	0	same	same	same	same	same	same	same	same
Municipal	−7	+55	+190	same	same	+41	+188	same	same
IOU	−4	+33	+64	same	same	+24	+63	same	same
Industrial	+9	−31	−41	same	same	−41	−41	same	same
Financial/Entrepreneur									
Actual price	6	−30	−12	same	−10	−08	−06	same	−05
No capacity credit	same	−25	−28	−25	−24	−24	−27	−24	−22
100% capacity credit after 1984	same	+11	+21	+19	+17	+11	+19	+17	+16
Increase license cost by 30%	same	−02	−02	same	same	−01	−02	same	same
Decrease license cost by 30%	same	+02	+02	same	same	+01	+02	same	same
Eliminate license cost	−2	+05	+06	same	same	+03	+06	same	same
Investment tax credit of 21% in 1980	same	+08	+19	same	same	+10	+19	same	same
Financial life of 50 yr in 1980	same	+05	+13	same	same	+07	+13	same	same
Tax life of 20 yr in 1980	same	+05	+11	same	same	+06	+11	same	same
Guaranteed price of approx $.05/kwh in 1980	same	+14	+22	same	+17	+12	+14	same	+12
Interest rate of 9% in 1980	same	+18	+48	same	same	+20	+47	same	same
No risk licensing in 1980	same	+03	+04	same	same	+02	+04	same	same
Regulatory/Entrepreneur									
Minor license delays	2	+04	same	same	−03	+03	same	same	−02
Double license delays	−3	−03	−01	same	+05	−04	−03	same	+03
Increase license requirement by 100% in 1984	same	−06	−05	same	+03	−04	−06	same	+01
Decrease license requirement by									

TABLE 3.—*Continued*

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
100% in 1984 (same as pre1969)	same	−07	+02	same	−02	+03	+02	same	−01
Exemption of SSH from license in 1980	same	+06	+02	same	−03	+04	+03	same	−02
Combined/Entrepreneur									
Investment tax credit of 21%, financial life of 50 yr, and tax life of 20 yr in 1980	same	+17	+48	same	same	+20	+48	same	same
Licensing and construction costs both at 9% in 1980	same	+18	+50	same	same	+21	+49	same	same

is needed. Utilities may not give developers capacity credits if the hydropower is not considered sufficiently reliable to provide dependable capacity.

The two most favorable policies in this set of policy runs are a guaranteed price of approx 50 mills/kwh after 1980 and a nominal interest of 9% instead of 12% in 1980.

According to the model, small-scale hydropower development appears to be moderately sensitive to adjustments in such parameters as investment tax credits, allowable tax lives, and financial lives. Furthermore, without considering inflation effects associated with delay, development is relatively insensitive to licensing costs.

A further observation that can be made from the financial runs is that the cost of developing small-scale hydropower is generally greater than the price currently being paid for it in any year. By the time the plant goes on line, however, the price being paid for the hydropower approximates the cost of its development. In all cases, the difference between the two prices is greatest in the early years of development. This indicates that cash flows may be negative in this early period.

Since municipalities, IOU, and industries have different tax and financial lives, debt/equity ratios, and returns on debt and equity, these types of developers are not expected to respond to financial policies as do the entrepreneurs. A few general conclusions, however, are applicable to all: (1) The known availability of a capacity credit in the future, even if not 100%, will spur development; (2) financial incentives and practices such as guaranteed (or even subsidized) prices, life-cycle costing, loans, increased investment tax credits, and decreased tax lives have significant positive effects on SSH development; and (3) licensing costs by themselves (i.e., not including effects of inflationary delays) have little effect on development.

Regulatory Policy Runs.—The model indicates that small-scale hydropower development is only weakly sensitive to licensing delays (e.g., time taken for nonFERC review, number of contested cases), licensing requirements (e.g.,

the requirement of a National Pollution Discharge Elimination System permit), or simplification of the regulatory process for hydropower licensing to that existing before the National Environmental Policy Act. This seems contradictory because both past and present developers generally have attempted to avoid licensing procedures, and in fact, most existing projects are not licensed (3). It can be deduced, then, that there must be some perceived or actual problems associated with licensing that are not modeled, such as the inflationary effect of delays, the intimidating effect of the licensing process, and some developers' lack of experience in legal matters. These perceived or actual problems require investigation.

It is interesting to note that decreasing licensing delays cause the initiation of development to occur later than otherwise (2 yr later in this run); the entrepreneur does not have to begin development plans so early because less time is needed to get the plant licensed. Similar licensing changes would be expected to have the same effect on IOU and municipalities. Since direct industrial users do not need licenses, they may be less affected by these types of policies.

Combined Financial and Regulatory Policy Runs.—Combined financial and regulatory policies resulted in more development than when only one type of

TABLE 4.—Applications from New England for Permits and Licenses or Amendments to Licenses Pending on April 14, 1979

Variable (1)	Municipal (2)	Industrial (3)	IOU (4)	Entrepreneur (5)	Rural coop (6)
Capacity, in megawatts	36.2[a]	8.6	28.3	5.26	20[a]
Number	6	1	2	5	2

[a]Capacities not given for several applications.
Source: FERC, Washington, D.C.

policy change was made (see Table 3). While the combined policies examined in this study always caused an increase in development, it is possible that some combined policies may have counteracting influences and thus cause no change in development or even hinder it. Many types of combined policies therefore need to be studied in order to determine their actual influences.

Summary and Policy Implications.—Considering the structure and limitations of HYDRO-I, the policy runs made with the model indicate that, from a financial point of view, the most promising development of small-scale hydropower is by municipalities and IOU. While significantly less attractive financially, development by private entrepreneurs also shows promise, particularly if given financial incentives. Development is not attractive from an industrial viewpoint because of the short payback periods required. With the exception of development by IOU, these results are reasonably consistent with what is actually occurring, although unique institutional factors may exist in New England that hinder development by IOU.

The model shows that in the year 2000, given the acceptable economic assumptions in HYDRO-I, it may become economically feasible for the three leading types of developers to develop sites costing approximately double the

present costs. Small-scale hydropower will generally only be developed now if developers are willing to accept the risks of using projected prices for the value of hydroelectricity when or soon after the plants go on line. Development may therefore be significantly encouraged if developers are assured of the future availability of capacity credits and fuel escalation clauses, or if they are guaranteed a fixed price, to be adjusted for annual inflation, consistent with cost projections for fossil fuel plants.

Since over the next 10 yr–20 yr some small-scale hydropower projects may show negative cash flows in the first few years after implementation, one way to encourage development might be to provide many small, short-term low interest loans over this period, rather than a few large, long-term, low interest loans. This possibility requires further investigation.

Single or combined financial incentives such as lifecycle costing, increased investment tax credits, low interest loans, decreased tax lives, and guaranteed prices can significantly spur the development of small-scale hydropower. The rate of increase depends on the type of developer.

There may be actual or perceived financial and institutional problems associated with the licensing process. This is suggested by the model's indication that licensing delays and costs by themselves do not seriously hinder hydropower development, even though most developers react negatively to the licensing process. This problem may act as a barrier to development and needs further study. It is suspected that the inflationary effects of the licensing delay and the complexity of the process are the major deterents.

Conclusions

A model has been presented of the economic, licensing, construction, and retirement factors or sectors that influence the development of small-scale hydropower at existing dams in New England. The model best represents development from the point of view of the entrepreneur. Given its limitations, the model is useful for financial and regulatory policy analysis. Some preliminary policy analysis has been examined. Future work will consist of improving the model's economic and licensing sectors and data base, adding environmental and social sectors, and modeling the impacts of the Public Utility Regulatory Policies Act of 1978 (PL-95-617) and other regulations implemented after the model was developed. This will be reported on in future papers.

Acknowledgments

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JOURNAL OF THE WATER RESOURCES PLANNING AND MANAGEMENT DIVISION

NAWDEX: Focal Point for Water Date Information[a]

By Melvin D. Edwards[1]

Introduction

Water data are collected and used today by hundreds of organizations involved in diverse missions. Identifying the appropriate organizations and obtaining needed data from them has often been a frustrating and time-consuming process. Valuable data are often not utilized because it is not known that they exist; needed data are frequently difficult to obtain within needed time frames; and considerable time can be wasted obtaining duplicate data from multiple sources. The National Water Data Exchange (NAWDEX) was established by the United States Geological Survey in 1976 to serve as a national program for cataloging and indexing water data that are available throughout the nation and to improve access to these data. This paper describes the services available through the program and how the program can be used as a focal point for acquiring information on data available from a large number of organizations.

Description of NAWDEX

NAWDEX has been developed as a confederation of organizations working together to improve access to water data. Organizations participate in NAWDEX by becoming members. Membership requires that a Memorandum of Understanding be signed between the organization and NAWDEX which defines the member's general commitment to take an active role in the program, to provide information on its data holdings, and to provide data from its holdings in response to requests.

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[1]Hydro., United States Geological Survey, 421 National Center, Reston, Va. 22092.

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Currently, over 190 organizations from the Federal, state, local governmental, interstate, academic, and private sectors participate as members. Four foreign organizations located in Brazil, Canada, and Mexico are also affiliated with the program.

As shown in Fig. 1, members are linked through a central program office located at the United States Geological Survey's National Center in Reston, Va. The central program office provides overall management of the program, develops data-exchange guidelines, develops and maintains central indexes of available data, develops and maintains systems and software needed for operation of the program, and coordinates a nationwide program of user services. Each

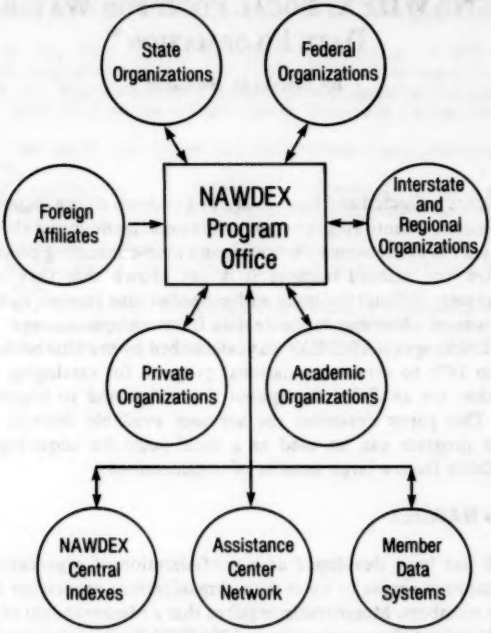

FIG. 1.—NAWDEX Organizational Structure

member designates one or more individuals to serve as direct points of contact with the program office on all matters related to NAWDEX, thereby, assuring continuing liaison and reliable communication with all participants in the program. This structure and mode of operation greatly facilitates the ability of NAWDEX to serve as a national focal point for information about available water data.

Centralized Indexing of Water Data

A critical factor in the acquisition and exchange of water data is the awareness of available data and the sources from which these data may be obtained.

It is not economically or logistically feasible to gather and store all water data at a central location. Therefore, a viable alternative is to maintain a central index that is readily and conveniently available to all users that will allow the user to quickly identify what data are available and where they may be obtained.

The NAWDEX program office maintains two computerized data bases for this purpose: (1) The Water Data Sources Directory; and (2) the Master Water Data Index.

The Water Data Sources Directory identifies organizations that are sources of water data or other environmental data pertinent to water-resource activities. For each organization, information is provided on office locations within the organization from which data may be obtained, alternative sources from which the organization's data may be obtained, the geographic areas for which data are available, the types of data available, and the media in which the data are available. The Directory is not restricted to sources of water data, but also identifies research organizations, users of data that produce subsequent information products, sources of other environmental data that may be pertinent to water-resources programs such as planning agencies, enforcement agencies, and others. Thus, it serves as a mechanism for providing information about a large number of organizations that contribute to environmental studies and programs. To date, over 700 organizations have been registered in the Directory and others are being added on a continuing schedule as information about them is gathered.

The Master Water Data Index identifies individual sites for which water data are available. For each site, the following information is provided: (1) The geographic location of the site; (2) the identification of the source organization; (3) the types of data available (surface water, ground water, or water quality); (4) the periods for which each type of data are available; (5) the major water data parameters measured; (6) the frequency of measurement of the parameters; and (7) the media in which the data are available. Over 370,000 sites for which water data are available from over 400 organizations have been identified, and new sites are being added on a continuing shedule.

Large volumes of areal or nonpoint data are also collected. Design specifications for a central index of these data are currently under development for the future inclusion of this information as a part of the NAWDEX information resources.

The Water Data Sources Directory and Master Water Data Index are designed for conjunctive use and are cross-referenced by organization and geographic locater codes. For example, the Index may be used to identify sites for which data are available within a project study area and the Directory can be used to identify office locations of the source from which the data may be obtained. Also, all data available for an organization may not have been indexed. The Directory can be used to identify the total data resources available from an organization as well as the amount of these data that have been indexed in the Master Water Data Index.

These data bases, then, serve as a central focal point for information about water data available nationwide from a large number of organizations. They are stored on the United States Geological Survey's central computer system at its National Center in Reston, Va., and are available for direct computer access by all NAWDEX service centers and NAWDEX member organizations that have a frequent, continuing need to have these data available for use.

Focal Points for Access to NAWDEX

Once data are known to be available, an adequate and effective system must be established to assure the timely exchange of data and information between data holders and users. To meet this need, NAWDEX has coordinated the establishment of a nationwide network of assistance centers. To date, 60 centers have been established in offices of member organizations located in 45 states and Puerto Rico. The locations of these centers are given in the following:

Alabama: Tuscaloosa
Alaska: Anchorage
Arizona: Tucson
Arkansas: Little Rock
California: Menlo Park
Colorado: Lakewood (Denver) and Ft. Collins
Connecticut: Hartford
Florida: Tallahassee, Miami, Orlando, and Tampa
Georgia: Doraville (Atlanta)
Hawaii: Honolulu (also serves American Samoa and Guam)
Idaho: Boise
Illinois: Champaign
Indiana: Indianapolis
Iowa: Iowa City (2 locations)
Kansas: Lawrence
Kentucky: Louisville
Louisiana: Baton Rouge
Maryland: Towson (serves Delaware and District of Columbia)
Massachusetts: Boston (also serves Maine, New Hampshire, Rhode Island, and Vermont)
Michigan: Lansing and Ann Arbor
Minnesota: St. Paul
Mississippi: Jackson
Missouri: Rolla
Montana: Helena
Nebraska: Lincoln (2 locations)
Nevada: Carson City
New Jersey: Trenton
New Mexico: Albuquerque
New York: Albany and Syosset
North Carolina: Raleigh
North Dakota: Bismarck
Ohio: Columbus
Oklahoma: Oklahoma City
Oregon: Portland and Salem
Pennsylvania: Harrisburg and Malvern
Puerto Rico: Ft. Buchanan (San Juan) also serves Virgin Islands
South Carolina: Columbia
South Dakota: Huron
Tennessee: Nashville
Texas: Austin
Utah: Salt Lake City (2 locations) and Logan
Virginia: Richmond and Blacksburg
Washington: Tacoma
West Virginia: Charleston
Wisconsin: Madison
Wyoming: Cheyenne and Laramie

These centers provide local and convenient access to the information, data and services available through NAWDEX. They provide direct assistance to users in identifying and locating needed data and making referrals to source organizations for data acquisitions.

All assistance centers, except four, have direct access to the Water Data Sources Directory and Master Water Data Index via computer terminals. Therefore, users can be provided with site-location listings, summary statistics, source addresses, and other information pertinent to the available data within

their area of interest. These centers also have direct access to the water data files of the Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) and can provide data from this system upon request. The NAWDEX program office in Reston, Va., the assistance center facilities of the Texas Natural Resources Information System (TNRIS) in Austin, Tex., the Utah Division of Water Rights in Salt Lake City, Utah, and the Center for Water Resources Research for Utah State University in Logan, Utah, serve as disseminating agents for water-quality data stored in the Storage and Retrieval (STORET) system of the United States Environmental Protection Agency (EPA). The NAWDEX program office also has the authority to provide direct computer access to the WATSTORE and STORET systems for a limited number of its member organizations. Members may also establish computer access to the NAWDEX data bases if desired.

Many additional systems and data services are available outside the NAWDEX

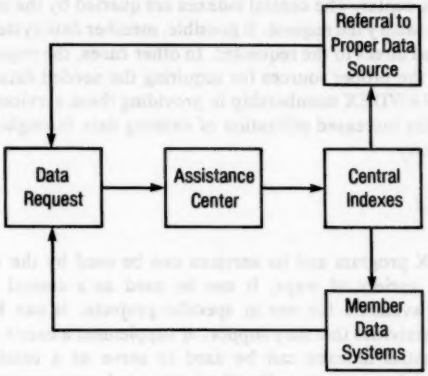

FIG. 2.—Typical NAWDEX Retrieval Request

assistance center network that contain information and data pertinent to water-resource programs. NAWDEX coordinates its activities with several of these systems and services and has established cooperative programs with them for the exchange of requests, data, and information to assure that a user of water data is provided maximum access to other environmental data and information that are available. Cooperative programs have been established with the Environmental Data and Information Service of the National Oceanic and Atmospheric Administration which includes the following: (1) The National Climatic Center; (2) the National Oceanographic Data Center; (3) the Environmental Science Information Center; (4) the National Geophysical and Solar-Terrestrial Data Center; and (5) the Center for Environmental Assessment Services. Independent organizations include the Water Resources Scientific Information Center (WRSIC) of the United States Department of the Interior and the Water Resources Document Reference Center of the Canadian Department of the Environment. Through these systems and services, access is provided to over 100 bibliographic

systems of other organizations and an index of over 10,000 environmental data files maintained by the Environmental Data and Information Service. Three assistance centers, (TNRIS), in Austin, Tex., the Water Resources Research Center of the Virginia Polytechnic Institute and State University in Blacksburg, Va., and the Water Resources Research Institute of Colorado State University in Ft. Collins, Colo., have direct computerized access to the bibliographic files of (WRSIC) of the United States Department of the Interior and support the other assistance centers by providing information from this system.

The NAWDEX assistance center network serves, therefore, as a focal point for access to many data bases including several major Federal water-data files, bibliographic files, and environmental data-index files. Several of the centers also serve as major focal points for access to data within their respective states, in addition to participating in the national-level NAWDEX program. Services are available to anyone. As shown in Fig. 2, a request may be submitted in writing, by telephone, or by personal visit to the NAWDEX program office or any assistance center. The central indexes are queried by the center to identify data available to satisfy the request. If possible, member data systems are accessed and data provided direct to the requester. In other cases, the requester is referred by the center to the proper sources for acquiring the needed data. The continued support of the NAWDEX membership in providing these services will contribute significantly to the increased utilization of existing data throughout the water-resources community.

Uses of NAWDEX

The NAWDEX program and its services can be used by the water-resources community in a variety of ways. It can be used as a central focal point for identifying data available for use in specific projects. It can help to identify data acquisition activities that may support or supplement a user's own acquisition activities. Its central indexes can be used to serve as a catalog or index or a user's individual data resources, thereby helping to better manage the resources. The indexes also serve as a valuable mechanism for communicating the availability of data or services to a large number of organizations. They also have value for many management functions such as supporting the coordination of water data acquisition activities among many agencies, defining the existence and overlap of data-monitoring networks; defining duplicate data acquisition activities; identifying additonal data activities that are planned or needed; and defining the relationship of data acquisition activities between various agencies in specific geographic areas. A wide variety of catalogs, printed indexes, numerical summaries, and other products can also be provided that are tailored to a requester's specific needs or interests.

Summary

NAWDEX has been operational since 1976. It is just now beginning to become widely known and utilized by the water-resources community. Its membership structure, its centralized indexes of available water data, and its nationwide network of assistance centers have proven successful in improving access to

available water data, increasing the utilization of these data, and simplifying access to data available from a very large number of collector and holding organizations. The program will continue to increase its information resources and expand its service capabilities. In this manner, it will continue to serve as an important focal point for information about water data available on a nationwide basis.

JOURNAL OF
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RESIDENTIAL WATER CONSERVATION

By J. Ernest Flack,[1] F. ASCE

INTRODUCTION

Water conservation is becoming increasingly a slogan for water utilities in the United States. Fast fading are the days when water was supplied in great abundance at prices of only a few cents/1,000 gal, or at no unit charge at all but delivered in any quantity desired at a flat rate. What caused this evolution from plenty to scarcity? Three factors seem to have come together to emphasize that water is a scarce commodity subject to competition. These are: (1) Increasing costs of raw water development; (2) higher standards of treated drinking water; and (3) scarcity of supply exacerbated by drought. This combination has resulted in attempts to stretch the available supply. If each user, on the average, used less water, then the available supply and delivery capabilities of the water system could serve more users. For instance, it has been estimated that the water savings that would result from metering Denver's 88,000 flat-rate customers would be enough to supply at least 25,000 new metered customers.

This paper attempts to describe various water conservation programs as combinations of different options that reduce water demand and then to evaluate the techniques and knowledge needed to implement them (7).

BENEFITS FROM REDUCING DEMAND

A water conservation program provides direct benefits to the utility and to the utility's customers. The benefits include reduced pumping costs, deferment of system expansion, increased life of existing capacity, and reduced hydraulic loading of sanitary sewer facilities. Water treatment benefits result from reduced energy and chemical costs and lowered residual-sludge volumes. In addition,

[1]Prof. of Civ. Engrg., Univ. of Colorado, Campus Box 428, Boulder, Colo. 80309.

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the attenuation of peak flows by conservation practices would allow scaled-down designs and lower system investment costs for those facilities designed to meet peak demands such as water treatment plants, pumping stations, and storage and piping in the distribution system (6). The customer can receive benefits through reduced energy bills for heating water and perhaps reduced water costs (passed along as decreased utility operating costs and lower plant investment expenditures).

Residential Water Conservation Methods

Water conservation can be defined as making more efficient use of existing supplies through structural, operational, economic and sociopolitical means. The need for residential water conservation was recognized by the National Water Commission which declared (14)

> In planning to meet future demands for municipal and industrial water, full consideration should be given to the possibilities for reducing water withdrawals by metering, by imposition of pricing systems that encourage more efficient use of water, by changes in building codes, by reducing leakage, and by other measures, as an alternative to increasing supply, or as a means for minimizing the necessary increase.

Public Law 92-500 implies a legal mandate for water conservation by announcing through regulatory fiat the "grant-eligible" portion of the total capacity of wastewater treatment facilities that the Environmental Protection Agency (EPA) will fund (4). More recently the President issued memoranda to heads of executive departments and agencies requiring implementation of changes to achieve water conservation in loan and grant programs for water supply and treatment, in housing assistance programs, and in agency operation of all kinds (13).

If implementation of water conservation programs is to be successful, a commitment is required from the water utility management; good relations must exist between the water-using public and the utility; and the water customer must believe that conservation is both necessary and desirable.

A recent Congressional Research Service study (11) has emphasized two problems in implementing water conservation programs: (1) The ingrained idea that per capita use of water must continually increase to maintain our standard of living; and (2) the failure to establish a price for water which is commensurate with its value in use. In the following sections some of the methods of attaining water conservation by urban users are summarized.

Structural Methods.—Through metering, flow control devices, and recycling systems, reduction in demand can be encouraged. The metering of customer usage normally causes the consumer to become more sensitive to price, i.e., customers who are charged for water on the basis of use will tend to restrict their use. Other system-wide structural means include reducing system-wide pressure, reuse of wastewater, and installation of hydraulic flow regulators which physically restrict the amount of water (flow rate) that can be delivered.

Recycling treated wastewater for public use or residential use may one day represent an important supply alternative. Reuse for irrigation and recreation purposes, as well as other selected uses, becomes more feasible as utility costs

escalate, treatment methods improve, and water supplies become more and more scarce.

The consumer can install water-saving devices, flow controllers, and recycle systems. Water-saving devices include plumbing fixtures and appliances that accomplish the same function as standard equipment but use less water. Flow-controlling devices reduce the pressure in the individual residence. Home recycle systems are based on segregation of wastewater flows in the home, usually into gray- and black-water components, and involve successive reuse, perhaps even with retreatment, of the gray-water component (5).

The individual consumer can reduce lawn-water usage through changes in horticultural practices of a physical or operational nature. The use of native species of plants and certain landscaping techniques can reduce sprinkling requirements. Installation of improved sprinkling equipment, drip irrigation, and similar systems permit the application of less water (3).

Operational Methods.—Operational methods of demand reduction are chiefly under the control of the utility. Leakage detection and repair and the implementation of use restrictions are the major operational means of water conservation. System leakage is responsible for large quantities of unaccounted-for water in some communities. Leakage repair improves system efficiency and increases water availability. Procedures are available to detect and correct most system leaks. These have been found to be cost effective in terms of the value of the water saved (9).

The implementation of restrictions for different categories of use is a common conservation technique. Residential water-use restrictions may be specifically addressed to exterior water uses such as lawn irrigation and the filling of swimming pools or, in more severe instances, to the total usage/customer.

The consumer can also implement the operational technique of demand reduction. One way is through leakage repair. The detection and repair of fixtures' leakage is principally the homeowner's responsibility.

In some utilities excess pressures increase usage and the rate of leakage. System pressure reduction to 50–60 psi (345 kN/m^2–414 kN/m^2) has been shown in several instances to reduce demand. Of course, it is necessary to guard against excessively low pressures as well. At the household level, utilities have required the installation of pressure reducers in the household tap if pressures are excessive, say above 60 psi (414 kN/m^2) (12).

Economic Methods.—Economic means of demand reduction can be accomplished solely through utility actions. The economic modes of water conservation include pricing policy, incentives, penalties, and demand metering. A constant unit price or an increasing block-rate structure, as contrasted with the typical flat rate or declining block rate, places increased cost on the use of additional increments of water. Incentives take the form of rebates, tax credits, or other rewards for conserving water. Penalties or fines can be imposed for the wasteful use of water. Demand metering is a pricing mechanism based upon measurement of incremental volumes in relation to time of use. That is, demand meters couple a structural device with peak-demand pricing to encourage reduced usage during peak-demand periods.

Socio-Political Methods.—Public education regarding conservation techniques is necessary in any demand reduction program. Instruction in how water is used and how various conservation alternatives would work are the keys to

their adoption. Development of a conservation ethic is essential to any successful water conservation campaign.

Other socio-political means include laws, such as building-code modifications that mandate the use of low water-consuming plumbing fixtures. By requiring water-saving equipment in all new homes and all remodeling plans, significant water-use reductions are virtually assured.

Water Conservation Programs: Water Savings Through Conservation

Combinations of the various water conservation alternatives previously mentioned can be designed to fit specific situations. All of the previously discussed conservation methods affect one another, and are not strictly additive; therefore, absolute savings cannot be predicted by adding up the savings of the methods adopted, but judgment must be used in estimating the total effect of a combined program. This is illustrated in the following.

Baseline Conditions.—To evaluate a program of water conservation a baseline was established against which savings can be measured. For illustrative purposes

TABLE 1.—Baseline In-House Water Use

Function (1)	Use	
	In gallons per capita per day (2)	As a percentage (3)
Toilet	25.0	40
Bath/shower	20.0	30
Lavatory/sink	3.0	5
Laundry	10.0	15
Dishwasher	3.0	5
Culinary	3.0	5
Total	64.0	100

Note: 1 gpcd = 3.78 lpd.

a residential community of 40,000 population with 10,000 dwelling units is assumed. The typical household has four members, two bathrooms, a dishwasher, and a clothes washer. The lawn size is assumed to be 8700 sq ft (809 m^2).

The home is not metered and the rate of sprinkling application is 2.8 ft of water/yr—well above the irrigation requirement of 1.9 ft (0.579 m) needed to meet the potential evapotranspiration less effective rainfall for a semiarid locale such as Denver, Colorado (1).

In-house uses for baseline conditions are assumed as given in Table 1, and total 64 gal/capita/day (gpcd). This is equivalent to 243 L/capita/day (lpcd). Average daily water use for the four-member household is 256 gal/day/dwelling unit (gpd/du) (970 lpd/du) domestic use plus 500 gpd/du (1895 lpd/du) sprinkling use or 756 gpd/du (2,865 lpd/du).

The ratio of maximum day to average day during the peak summer lawn-watering period is taken as 2.1, and the peak hour to average day ratio as 5.3 (15). These result in a maximum day demand of 1,588 gpd/du (6,019 lpd/du) and peak hour use of a little more than 4,000 pgd/du (15,160 lpd/du). Sanitary

sewer flows are equal to the domestic usage of 256 gpd/du (970 lpd/du). Return flow from excess lawn irrigation would be 160 gpd/du (606 lpd/du).

For the hypothetical city with a population of 40,000 the per capita, per dwelling unit and total water usage including return flow is shown in Table 2. Total annual demand would be 2,760,000,000 gal (10.4×10^6 m^3) and return flow would be 1,520,000,000 gal/yr (5.75×10^6 m^3).

Metering.—Having established baseline conditions on a flat-rate, nonmetered basis, the effects of metering can now be enumerated. While it seems reasonable that metering would reduce domestic usage somewhat (especially in older residences) because of leakage repair and better maintenance of plumbing fixtures, the in-house usage values given in Table 1 are relatively conservative and for this reason no reduction in this component's demand is assumed. Lawn sprinkling would, however, be affected and it is assumed that irrigation would drop to

TABLE 2.—Residential Water Demand—Unmetered (40,000 population—10,000 households)

Sector demand (1)	Daily Demand or Flow		
	Per capita, in gallons (2)	Per household, in gallons (3)	Total, in millions of gallons (4)
Average annual:			
In-House	64	256	2.56
Sprinkling	125	500	5.00
Total	189	756	7.56
Maximum day	397	1,588	15.88
Maximum hour	1,000	4,000	40.00
Return flow:			
Sanitary sewer	64	256	2.56
Irrigation	40	160	1.60
Total	104	416	4.16

Note: 1,000,000 gal = 3785 m^3; 1 gal = 3.78 L.

be just equal to the irrigation requirement of 1.9 ft/yr (0.58 m/yr). The consequence of this would be to reduce the return flow from lawn irrigation to zero if, as assumed, the water is entirely consumptively used. Total efficiency in lawn watering is not likely, however, and some return flow is assumed equivalent to 10 gpd/du (38 lpd/du) which is 3% of the applied rate.

The result of metering on components of demand is shown in Table 3. Metering has the effect of reducing total demand by 21%, sprinkling by 31%, and return flow by 29%. Metering has been shown to be cost effective in terms of water saved if costs of installation are reasonable (15).

Water-Saving Household Devices.—Water-saving household devices cover a wide range of plumbing fixtures and household appliances. For retrofitting, the following are sufficiently cost effective, easy to install and maintain, and not disruptive to existing water-use habits: (1) Plastic bottles or dams in the toilet water closet to reduce water usage per flush; (2) low-water using shower heads; and (3) faucet aerators.

Plastic bottles or dams are estimated to save from 4,000–6,000 gal/yr/household (15,200–22,800 L/yr/household; shower heads save about 12,000 gal/yr/household (45,600 L/yr/household), and aerators save about 3,000 gal/yr/household (11,400 L/yr/household). The total savings are estimated at 20,000 gal/yr/household (76,000 L/yr/household). All of these devices are cost effective even at very low water prices (15).

For these devices to be effective, it is necessary that they be installed in a large percentage of the households. This is not difficult to attain in new housing, where plumbing and building codes can require the devices. For retrofitting, however, a concerted public-education program is necessary, as is the ready availability of the devices at little or no cost to the customer. Recent research has shown that about 50% of the households questioned indicated they would install water-saving devices if these were made available at little or no cost (15).

TABLE 3.—Residential Water Demand—Metered (40,000 population—10,000 households)

Sector demand (1)	Daily Demand or Flow		
	Per capita, in gallons (2)	Per household, in gallons (3)	Total, in millions of gallons (4)
Average annual:			
In-House	64	256	2.56
Sprinkling	85	339	3.39
Total	149	595	5.95
Maximum day	313	1,252	12.52
Maximum hour	790	3,160	31.60
Return flow:			
Sanitary sewer	64	256	2.56
Irrigation	10	40	.40
Total	74	296	2.96

Note: 1,000,000 gal = 3785 m^3; 1 gal = 3.79 L; assumed price is 43¢/1,000 gal (11.3¢/1,000 L).

The water savings if 50% of the 10,000 households in the example installed such devices could exceed 100,000,000 gal/yr, or about 14 gpcd (50 lpcd). This would be enough water to serve about 600 new customers. The residential water demand for the hypothetical community with metered services and installation of household devices is shown in Table 4. The combined result of metering and water-saving devices is to reduce total demand by 25% and return flow by 35%.

Pricing.—The use of pricing policy can be an effective tool for achieving water conservation. The economic incentive for using a smaller amount of water is dependent on consumer attitudes and needs, as reflected in the elasticity of demand. Economic theory of demand usually describes two kinds of elasticity, or the measure of change in demand with change in price. Income elasticity is related to the income of the consumer and, in general, indicates that for

nonessential commodities a consumer with a lower income will modify his demand more than a consumer with a higher income.

Price elasticity relates demand with price, is expressed as $\Delta Q/Q \div \Delta P/P$ and measures the change in demand that occurs for every change in price, given a price-demand relationship. In terms of residential use in-house demand is less price elastic than lawn sprinkling, i.e., with a given price increase the relative change in household use will change (decrease) less than sprinkling usage. Table 5 gives some price elasticity values for various categories of demand. In-house water use is considered essential and is not every responsive to price change. Exterior lawn watering use is somewhat less essential and is, therefore, more responsive to price changes. The elasticity for both these categories is always negative and less than unity, but its magnitude varies geographically and with specific use.

TABLE 4.—Residential Water Demand—Metered with Devices (40,000 population—10,000 households)

Sector demand (1)	Daily Demand or Flow		
	Per capita, in gallons (2)	Per household, in gallons (3)	Total, in millions of gallons (4)
Average annual:			
In-House	57	229	2.29
Sprinkling	85	339	3.39
Total	142	568	5.68
Maximum day	284	1,136	11.36
Maximum hour	716	2,862	28.62
Return flow:			
Sanitary sewer	57	229	2.29
Irrigation	10	40	.40
Total	67	269	2.69

Note: 1,000,000 gal = 3785 m^3; 1 gal = 3.79 L.

Pricing theory and response have been investigated by many investigators. Pricing methods have been devised in an effort to reduce the quantity of water demanded, but more typically they are used to proportion the costs equitably among consumers.

Peak demand rates and increasing block rates are two pricing structures that can promote water conservation. One procedure is to charge an extra fee for water used above some base allotment computed for each customer individually. For instance, a residential user may be charged significantly more per unit of water demanded any time his monthly usage exceeds 130% of his average winter monthly demand. Another conservation scheme is increasing block rates that charge large water users higher rates for additional units.

As an example of the water savings that can result from a price increase, assuming the elasticities of Table 5 are applicable, Table 6 shows the residential water demands for the totally metered community whose demand is given in

Table 3 at water prices of \$0.43/1,000 gal (11.34¢/1000 L) and at \$0.86/1,000 gal (22.64¢/1000 L). The net result of the doubling of water prices is a 32% reduction in residential demand.

Water-Use Restrictions.—The imposition of water-use restrictions is essentially a short-term method of conserving water. When water supplies reach a level at which officials project that there may not be enough water to meet near-future demands, voluntary restrictions are usually instituted. These may later be made mandatory. The primary difference between this conservation method and the others discussed is that restrictions inconvenience the water consumer, whereas the other methods are designed to inconvenience the customer as little as possible. The effect of restrictions is not included in this example, although it might be anticipated that a mandatory system of alternate day watering could reduce the sprinkling demand as given in Table 2 (unmetered) by as much as 30%.

Return Flow Implications.—The effect of urban water conservation on downstream receiving streams can be an important consideration especially in low-flow periods. The effects of conservation are of two kinds. One is the reduction in sewage effluent entering the receiving stream. In many locations downstream direct flow and storage appropriations are dependent on these effluent return

TABLE 5.—Price Elasticities (2,10)

Demand section (1)	Elasticity (2)	Source (3)
Residential	−0.225	(10)
Domestic	−0.26	(2)
Sprinkling (West)	−0.703	(10)
Average day	−0.3953	(2)
Maximum day	−0.388	(10)

flows. A municipal utility may be counting on their effluent to meet the rights of senior downstream appropriators while the city diverts water upstream under a junior appropriation. In either case, any reduction in the effluent discharge can adversely affect the downstream water users—in the first case by reducing the amount available to downstream junior appropriators and in the second case by either requiring reduced diversions upstream by the utility or by the release of storage water downstream to meet senior rights.

The second effect of a conservation program is the reduction in lawn watering. Since an effective conservation program can reduce watering to a level at or below the consumptive use requirement for a good lawn, the deep percolation and runoff components of applied water are virtually eliminated. These excess waters either recharge the ground water or enter the storm sewers and other channels leading to a receiving stream. If the ground water is hydraulically connected with the receiving stream, the effect on the stream is the same as that of a reduced discharge to the stream.

The result of a water conservation program that reduces in-house usage by toilets, showers, faucets, and washers will result in reduced sewage flow. While this may benefit the hydraulic loading on the sewage treatment plant, it can

adversely affect downstream appropriations. Conservation programs that reduce lawn watering may essentially eliminate this source of water from storm sewers and ground water and affect downstream appropriations of both surface and ground water.

The quantity of the decreases in return flow as a result of a conservation program is difficult to evaluate accurately because the analysis is dependent on hydraulic, hydrologic, and geologic conditions that exist at a specific site, but as noted in this example the effect of metering alone was to reduce return flow from 41,600,000 gal/day to 29,600,000 gal/day (157,700,000 L–112,200,000 L).

TABLE 6.—Change in Daily Residential Water Demand with Price (40,000 population—10,000 households)

Demand sector (1)	Demand, at $0.43 per 1,000 gallons,* in millions of gallons (2)	Assumed elasticity (3)	Demand, at $0.86 per 1,000 gallons, in millions of gallons (4)	Difference, in millions of gallons (5)
Residential:				
Household	2.56	−0.225	1.98	0.58
Sprinkling	3.39	−0.395	2.05	1.35
Totals	5.95		4.03	1.92

*From Table 3.

Note: 43¢/1,000 gal = 11.3¢/1,000 L; 86¢/1,000 gal = 22.6¢/1,000 L; 1,000 gal = 3780 L.

TABLE 7.—Water Conservation Savings

Practice (1)	Annual saving per household, in gallons/year (2)
Metering (if flat rate)	59,000
Devices (toilet, shower, faucet)	10,000
Double price (43¢/1,000 gal–86¢/1,000 gal)	70,000
Judged combined program	130,000

Note: 1,000 gal = 3,780 L.

Effects of Combined Water-Conservation Programs.—The water savings resulting from the combination of different conservation practices of metering, water-saving devices and the doubling of price is not the addition of the individual items because some of the practices affect consumer response in the same way. For instance, raising the price for water has some of the same effects on water use as device installation, and it is doubtful that, after water-saving devices are installed, doubling the price of water would result in as large a savings as indicated in Table 6. Table 7 gives a summary of the water savings

possible on a per household per year basis for the three water-conservation programs individually and for their judged combined effect.

Effect of Combined Conservation Programs on Metered Revenue.—Based on the values just presented, the before and after metered revenue picture can be illustrated. The total demand of the example community of 2,172,000,000 gal (8,232,000,000 L) at 43¢/1000 gal (11.3¢/1000 L) before conservation would produce $934,000 in revenues/yr. After conservation, the demand of 1,370,000,000 gal (5,200,000 L) at 86¢/1000 gal (22.6¢/1000 L) would equal $1,178,200 or an increase of $244,200 or 26% in the revenue from residential users. Of course, if demand did not drop as much as estimated, revenue would be even higher. On the other hand, water savings from installation of water-savings devices only, with the original price of water left intact, would result in a $43,000/yr loss in revenue. Ignoring elasticity effects, this loss could be recovered by a small price increase.

Conclusions

The effect of the combined water conservation programs illustrated here, i.e., metering plus devices and doubling the price, is to reduce domestic use from 64 gpcd (243 lpcd) to 57 gpcd (216 lpcd) by the use of meters and water-saving devices (if installed in 50% of all residences), and further to reduce domestic use to 43 gpcd (163 lpcd) by doubling the price of water. Lawn sprinkling would be reduced from 85 gpcd (322 lpcd) to 51 gpcd (193 lpcd) by the price increase. Overall usage would drop from 149 gpcd (565 lpcd) to 100 gpcd (379 lpcd) or a 33% decrease.

Three cautions to accepting these values need emphasis. They are the assumptions that: (1) The elasticities of demand are correct; (2) the programs are largely additive; and (3) 50% of all households would install and keep in good repair the water-saving devices.

Peak day to average day ratios would probably stay about the same under the conservation programs, with the peak day demand decreasing proportionately with the reduction in average day demand.

A loss of revenue would be the result of installing water-saving devices but revenue would increase markedly due to doubling the price of water. The combination of both practices would result in a sizable increase in revenue.

Reductions in return flow because of implementation of water conservation practices could have important implications to downstream water users, especially in water-scarce areas of the western United States.

Imposition of various water conservation programs either singly or in combination can result in significant reductions in residential water demand, but secondary effects on revenue production and return flow should enter the decision-making process regarding adoption of any water conservation program.

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COOPERATIVE WEATHER MODIFICATION PROGRAM[a]

By John T. Carr, Jr.[1]

INTRODUCTION

With the discovery shortly after World War II of the artificial formation of ice crystals and the subsequent development of cloud-seeding techniques, attempts were begun to adapt the new technology to the enhancement of rainfall. A number of operational projects were begun in various sections of the United States, and by 1970 three commercial cloud-seeding programs were underway in Texas. During the same time some of the commercial projects were being evaluated as to the effectiveness of cloud seeding, several scientific experiments were being carried out as well. Yet, thus far the results of these endeavors have been varied and indecisive.

More recently, a new and concerted endeavor is being made by the Federal government in cooperation with various states and local entities to determine what occurs after the application of various cloud-seeding techniques on an assortment of cloud types. This ambitious program of research and development in weather modification has been named the High Plains Cooperative Program (HIPLEX).

WHAT IS HIPLEX?

The HIPLEX program is a Federally sponsored research effort in the field of weather modification in the United States high plains states. It is part of the United States Department of the Interior's Project Skywater, which is designed

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[1]Chf., Weather Modification and Tech. Section, Tex. Dept. of Water Resources, Austin, Tex. 78701.

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to develop an effective technology for precipitation management to serve the nation's freshwater supply needs. The goals of the HIPLEX program are to establish both a verified, working technology and an operational management framework capable of producing additional rain from cumulus clouds in the high plains states.

Early in 1973, the Bureau of Reclamation's Office of Atmospheric Resources Management initiated the HIPLEX program as a joint effort involving state and local participation. In 1974 the Bureau entered into cooperative agreements with interested high plains states and selected three experimental sites representative of the northern, central, and southern sections of the great plains. These sites are located in Montana, Kansas, and Texas, with Big Spring being selected as the focal point of activities in Texas.

Texas HIPLEX Project Area

To promote weather modification research in the high plains of Texas, the Bureau entered into an agreement with the Texas Department of Water Resources, whereby the HIPLEX program in Texas would be a cooperative effort, with state and local groups sharing in the planning, operational control and support aspects of the program. An area of west Texas, which includes the target area of the Colorado River Municipal Water District's weather modification program, was selected as the Texas HIPLEX study site. Of the sites given consideration in Texas, this site was given top priority by the state and was determined to be representative of the crops, climate, and water needs of the region.

The Bureau of Reclamation provides financial and technical support to the Texas HIPLEX program. The design and conduct of the program are coordinated by the Bureau of Reclamation so that the results obtained can be integrated into the overall HIPLEX program in an optimum manner. Some of the equipment being used in the program, including a weather radar system, is furnished by the Bureau of Reclamation.

HIPLEX Objectives

The scientific and technical objectives of the Texas HIPLEX program are to develop a refined precipitation management technology that may be applied to produce additional rainfall on the Texas high plains.

The specific objectives are given in the following:

1. Scientific—(a) Acquiring data to establish a cloud and precipitation climatology of the region; (b) learning more about the relationship between large-scale (synoptic) weather conditions (e.g., cold fronts, squall lines) and storm-cloud populations; (c) identifying smaller-scale conditions and relating them to cloud development; and (d) examining various properties and processes (both microphysical and dynamic) of selected clouds.
2. Technical—(a) Increasing the meteorologist's ability to estimate precipitation from clouds using radar; (b) evaluating the behavior of cloud systems in the project area using measurement systems now available; and (c) developing better observational methods to accomplish present goals and future needs of the Texas HIPLEX program.

Funding

Funds for the Texas portion of HIPLEX have been allocated annually by both the Bureau of Reclamation and the state of Texas. Using available Federal and state funds, the Texas Department of Water Resources has contracted with research groups for HIPLEX-support services.

Experimental Basis

Previous investigations have shown that clouds contain tiny ice crystals or water droplets (or—as is common in the Texas high plains during the spring and summer—a combination of both). Dust, smoke, salt, and other particles in the air serve as nuclei around which the crystals and droplets form from available moisture in the atmosphere. Some of these microscopic particles serve as condensation nuclei on which water vapor condenses to form cloud droplets, while others act as ice nuclei on which condensed water freezes (or in some cases ice crystals form directly from water vapor). Generally, in the high plains region there is an abundance of condensation nuclei but a scarcity of ice nuclei available in the atmosphere.

The HIPLEX experiment is based on the idea that man can assist nature in the rain-making process through proper cloud-seeding management based on solid scientific fact. The results of the HIPLEX experiment may suggest that certain clouds have too few nuclei to effectively trigger the precipitation process. By furnishing appropriate nuclei through "seeding" at the proper time and place and in the proper amounts, these clouds may realize increased rainfall on the ground. The HIPLEX experiment is to identify the environmental conditions in which convective clouds can be stimulated to grow larger, rain earlier, and last longer through controlled seeding. Two types of cloud-seeding which may be employed include the addition of condensation nuclei and freezing nuclei. Consequently, this additional growth of the cloud allows more water to be processed longer and more efficiently than would have occurred naturally.

Operations Plan

Prior to beginning the series of field experiments each spring, an operations plan is devised which sets forth the procedures to be followed when cloud-seeding activities begin. In addition, this plan specifies the work of each organization participating in the field exercises and assists program administrators in ensuring that all of the work performed is closely coordinated.

HIPLEX Contractors

Following is a description of the activities of the participants in the Texas HIPLEX program, as well as an explanation of how these activities fit into the overall objectives of the program.

The State of Texas.—The Texas Department of Water Resources is Charged by Chapter 18 of the Texas Water Code (formerly the Texas Weather Modification Act of 1967) to regulate weather modification activities in Texas. Chapter 18 also provides that the Department promote research and development in the

field of weather modification. To this end, the Department's predecessor agency, the Texas Water Development Board, entered into the 1974 Agreement with the Bureau of Reclamation to cooperate in the HIPLEX Program.

Under the terms of this agreement, the Department contracts for services in support of HIPLEX. The contractors and their respective work programs are described in the following.

The Department obtains advice on all matters related to weather modification through the Weather Modification Advisory Committee, which consists of five members—an atmospheric scientist, a legal authority, an engineer, a businessman, and a farmer/rancher.

The Department operates a meteorological facility at Big Spring Municipal Airport (the base of HIPLEX field operations) to provide on-site forecasting support services for this cloud-seeding experiment. Surface and upper-air weather data are analyzed by an experienced Department meteorologist, and from these analyses forecasts are prepared and issued during the field operations phase of the program. The field operations phase typically extends for two or three months during the late spring and summer. The on-site meteorologist also contributes to the performance of HIPLEX program objectives by taking photographs of clouds, making weather observations, and conducting studies and evaluations of the forecasting technology used in the HIPLEX program. Another Department meteorologist serves as manager of the field operations.

A very important aspect of the Department's work is to evaluate the potential economic benefits of weather modification to the state. Specifically, studies are in progress to determine how much economic value can be expected from a controlled increase in rainfall and who will realize the benefits. The initial phase of the comprehensive evaluation deals with estimating the value of additional crop yields resulting from additional rainfall, with the direct effects realized as increases in income to farmers. A second phase of the study describes the effects of additional rainfall on rangeland forage production, the effects of that forage production on the livestock industry, and the impact of that livestock production on the economy of the area. A third phase of the evaluation focuses on effects other than agricultural, with emphasis on the effects of increased rainfall on the level of municipal and industrial water supplies and water-use patterns of the recreational use of area reservoirs.

Colorado River Municipal Water District.—To ensure the optimum concentration of artificial ice crystals in clouds determined to be likely candidates for rainfall stimulation, the cloud-seeding agent must be placed in the cloud in the right amount, at the proper location, and at the appropriate time. Placement of the artificial seed (silver iodide in the HIPLEX Program) in the cloud is accomplished with aircraft especially equipped for cloud-seeding purposes.

Under contract with the Texas Department of Water Resources, the Colorado River Municipal Water District provides two aircraft (a pressurized Navajo and a Piper Aztec) that are equipped with silver iodide flar racks. Flares, when ignited, dispense the cloud-seeding agent as the aircraft flies either through, above, or at the base of the cloud. The pilot of each aircraft is advised of the area where suitable clouds are likely to be found by the Chief Scientist, who uses radar to determine the location and intensity of developing thunderstorms. In addition to performing cloud-seeding activities, the aircraft also serve as airborne measurement platforms; a variety of data collected with special

instrumentation enable HIPLEX researchers to learn much about the nature of clouds in the HIPLEX region.

The District also provides the services of a radar meteorologist, who operates an FPS-77 radar unit at the Big Spring Municipal Airport in support of HIPLEX cloud-seeding and sampling missions.

In addition to providing aircraft, the services of pilots and a radar meteorologist for the conduct of cloud-seeding activities, the District also monitors an extensive network of recording rain-gages for the collection of rain-gage data. These gages are strategically located throughout the Texas HIPLEX study area to furnish data for determining when, where, and at what intensity rain fell within the project area.

Also, as a part of the Texas HIPLEX program, the District operates a rawinsonde unit from the operations center at Big Spring Municipal Airport. The rawinsonde unit consists of a balloon-borne package which transmits upper-air data (pressure, temperature, and relative humidity) as it rises aloft, to a ground-based tracking antenna. Wind speed and direction are computed at selected altitudes. Rawinsonde data are used for planning the daily cloud-seeding operations by providing a real-time view of the vertical structure of the atmosphere as well as for analysis and evaluation purposes.

Meteorology Research, Inc.—Meteorology Research, Incorporated (MRI) operates a Navajo cloud physics aircraft to collect and process certain data in accordance with procedures established by the Bureau of Reclamation. The MRI Navajo provides data on ice crystal concentration and liquid water content measured within selected clouds. On-board data processing equipment allows project personnel to be informed of cloud characteristics in real-time.

Texas Tech University.—The weather radar system is one tool the meteorologist uses to observe the location and concentration of liquid water and ice particles in convective clouds.

One of the objectives of the HIPLEX program is to utilize radar to examine the precipitation characteristics within convective clouds. Radar meteorologists of Texas Tech University (TTU) operate a 5-cm Skywater radar system, which is located at Howard County Industrial Park in Big Spring, as part of the observational network supporting the HIPLEX program. The Skywater radar unit, on loan for use in the HIPLEX program, is the property of the Bureau of Reclamation.

Data from this radar system are used to estimate rainfall rates from convective clouds, and in addition, the radar permits the determination of the characteristics of radar echoes from clouds within its range. Furthermore, the system indicates the heights of the tops of these cloud echoes.

Data gathered by the radar system are recorded digitally on magnetic tape, displayed on a color tube and photographed using 16-mm color film. These data are then examined in detail on the display tube and by computer analysis. The analysis of radar data provides an insight into various local cloud and rainfall behavior patterns which include: (1) Timing of seeding; (2) seeding effects on cloud tops; (3) organizational characteristics; (4) intensity and area variations; (5) total rainfall characteristics; area rainfall estimates; and (6) area rainfall characteristics.

The availability of photographs taken by meteorological satellites, orbiting many miles above the earth's surface, offers the atmospheric scientist a unique

view of the behavior of interacting cloud systems over the Texas high plains.

As part of the Texas HIPLEX Project, meteorologists at TTU examine photographic imagery from the Geostationary Operations Environmental Satellite (GOES) to determine the relation of individual clouds and cloud systems to various synoptic patterns and atmospheric conditions. These satellite photographs provide a finely resolved and detailed view of the tops of those convective cloud systems from which parameters important to the experiment can be derived.

Researchers at TTU are analyzing the GOES photographic data in hopes of recognizing from the satellite viewpoint the typical cloud features and processes that are active over the Texas HIPLEX site. These data will permit the TTU meteorologists to monitor the behavior of interacting clouds to determine if cloud merger leads to significant vertical growth of the clouds in the study region.

Radiance measurements from the GOES satellite will permit the TTU meteorologists to determine a number of physical cloud properties, such as the height of the tops of the cloud systems. Furthermore, it is hoped that these radiance data will reveal the phase of the water substances (e.g., ice, liquid, or a mixture of both) which constitute the uppermost portions of these cloud systems.

Using rainfall data collected by the specialized Texas HIPLEX recording rain-gage network and by the standard weather-observing network of the National Weather Service, TTU scientists are developing a precipitation climatology for the Texas HIPLEX region. Data having as fine a resolution as 15 min are analyzed to determine the frequency, intensity, and areal extent of rainfall occurrences within the study area. This endeavor will provide valuable insight to the types of rains which can be expected from various storm systems that migrate into or develop within the Texas HIPLEX area.

Texas A&M University.—By contract with Texas A&M University (TAMU), the Department is provided with the services of a chief scientist. The chief scientist's duties consist of coordinating all HIPLEX-related activities to ensure that these activities contribute to HIPLEX program objectives.

The Bureau provides in addition to the Skywater radar system, a network of 25 fully automated surface weather stations that measure wind movement, temperature, pressure, humidity, and rainfall at strategic points within the Texas HIPLEX project site. These stations record weather data at 5-min intervals, then transmit the data each hour to the Bureau's computer system in Denver by way of an orbiting weather satellite and a ground-receiving station on the Atlantic coast. The virtually real-time data enables the project forecaster to quickly analyze developing weather conditions and predict more accurately the occurrence of convective cloud systems. The 25 automatic weather stations were installed and maintained by the TAMU contingent with technical advice and assistance being provided by the Bureau.

Convective cloud systems (the principal source of rainfall in the high plains of Texas during the spring and summer) usually are relatively small in size, 50 km or less in diameter and thus "mesoscale" in nature. Mesoscale cloud systems cannot be studied effectively using conventional upper-air data which are collected by a much larger scale network. A study of these cloud systems requires a special program of data collection to ascertain how, where, and when those clouds will develop. Of particular importance is the need to accurately

measure the life history of these naturally formed clouds, including information such as periods of existence and rates of growth.

Meteorologists in the Department of Meteorology at TAMU are endeavoring to meet this need through a program of collecting and analyzing mesoscale data. Since 1976, part of the experimental phase of the Texas HIPLEX program has consisted of a concentrated effort of several weeks duration to study the organization of mesoscale cloud systems and to examine the interactions between cloud systems and between the systems and the environment. Among these parameters are temperature, moisture, pressure, and wind speed and direction. A rawinsonde network operates within the project area and probes the atmosphere as high up as 19,000 (about 62,000 ft), thus enabling the development of profiles of the atmosphere for any desired period of time.

The mesoscale data gathered during the field programs are processed and analyzed by researchers at TAMU between field operation seasons. It is expected that an analysis of these data will shed light on the localized processes in the atmosphere that are responsible for the development and growth of thunderstorms and other convective clouds.

In addition to the mesoscale study, scientists at TAMU analyze radar film of the Texas HIPLEX region for the construction of a "radar echo climatology." This climatology provides information on the size and times of occurrence of radar-detected storms that develop in the region during the cloud-seeding season, as well as the duration of the life cycle and the speed and direction of movement of these "echoes." If previous occurrences of storms in the area can serve as guidance for what is likely to happen in the future, then this climatology will be very useful in determining when and where cloud seeding should be performed. Furthermore, the study of radar echoes associates their occurrence to certain atmospheric conditions such as cold fronts and low-pressure storm centers. This aspect of the study will aid in the prediction of occurrences of cloud systems.

Looking Ahead

Through a considerable amount of data on the weather characteristics of the Texas high plains has been collected and analyzed since the commencement of field measurements in 1975, more experimentation, particularly in the areas of seeding mechanisms and cloud behavior, is needed to remove the uncertainty about the potential of weather modification for increasing rainfall. The goal of the HIPLEX program is to learn how cloud seeding can be employed efficiently, economically, and on a socially accepted basis to increase precipitation in water-short areas of the high plains region.

Results

Although much has been learned about cloud behavior before and after controlled seeding and the radar equipment used in 3 yr of the 4 yr reported on has been twice upgraded, resulting in much improved reflectivity measuring, collecting, and cataloging techniques, the data set is not extensive enough to yield statistical significance. The natural variability of rainfall in the project area often is 25%–40% greater or less than the historical average, on an annual

basis. under these conditions, a determination of the statistical significance of the HIPLEX project in Texas cannot be made until the data base is extended sufficiently to overcome the noise. In the meantime nonstatistically significant measures, such as favorable crop response and increased annual rainfall averages must be relied upon for encouragement to continue the HIPLEX program. Until statistical significance can be achieved. Refs. 1, 6, and 10 directly address these two measures.

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JOURNAL OF THE WATER RESOURCES PLANNING AND MANAGEMENT DIVISION

STATUS OF SOUTHEAST RIVER BASIN WATER RESOURCES[a]

By Clair P. Guess, Jr.[1]

INTRODUCTION

The purpose of this paper is to provide a general status report on water resources planning and management in the southeastern United States as documented in the 1975 National Water Assessment. This evaluation also is intended to draw upon the recommendations, as they may have been realized, from the United States Study Commission on Southeast River Basins, as they are contained in the 1963 Plan for Development of the Land and Water Resources of the Southeast River Basins.

The Second National Water Assessment of 1975 for the South Atlantic-Gulf Water Resources Region, concerned with specific problem analysis (see Fig. 1), in general terms, points to an overall well-balanced supply demand ratio for water. One would expect such a conclusion in a region having from 41 in.–80 in. (104 cm–103 cm) of average annual rainfall where most streams drain from the highest mountain elevations, through the foothills, and continue to the sea in river basins that are quite parallel, and generally flow from north-northwest to south-southeast.

However, there are some sharp seasonal variations in specific areas that point to a periodic lack of supply to meet demands. It is also true that demands are often neglected where supplies are inadequate for development. In such cases, economic growth is restrained and social well-being is under stress.

[a]Presented at the October 22–26, 1979, ASCE Annual Convention and Exposition, held at Atlanta, Ga.

[1]Executive Dir., South Carolina Water Resources Commission, P.O. Box 4515, 3830 Forest Drive, Columbia, S.C. 29240; also Chmn., Southeast Basin Inter-Agency Committee; and First Vice Chmn., Interstate Conference on Water Problems.

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Specific Problem Areas

Specific areas where severe problems have been identified (and suggested for more in-depth study), according to the South Atlantic-Gulf Water Resources Report in the National Water Assessment of 1975–2000, include:

1. Water Quantity, Fresh-Surface—(a) Chowan-Lower Roanoke in southeastern Virginia (Hampton-Roads Portsmouth); (b) north central North Carolina:

FIG. 1.—South Atlantic-Gulf Region

highly urbanized areas of Winston-Salem, Greensboro, High Point, Burlington, Raleigh, Chapel Hill, and Ashboro; (c) southeast North Carolina: six counties in the lower Cape Fear Basin; (d) Saluda Subbasin: a highly industrial corridor along Interstate 85 through northern South Carolina; (e) Apalachicola-Chattahoochee-Flint (Atlanta Metropolitan Area): expanding population and industrial

growth in the Atlanta metropolitan area appears to have reached a crisis unless additional water supplies can be obtained outside of the basin or by redesignating the use of waters from a Federal hydro-electric reservoir (Lake Lanier); (f) Black Warrior-Cahaba in Alabama: interbasin transfers are seasonally creating extremely low flows; and (g) Mobile and Pascagoula: high water demands in competition with a single source.

2. Water Quantity, Ground—(a) Franklin Area, Virginia: serious over-pumpage lowering water tables and increasing chlorides in ground-water aquifers 15 miles (24 km) away; (b) Beaufort County Area, North Carolina: ground-water withdrawals to accommodate phosphate dry open pit mining has lowered the piezometric surface over an area of more than 800 sq miles (2,072 km^2); (c) Suwanee and Apalachicola-Chattahoochee-Flint (southwest Georgia): heavy

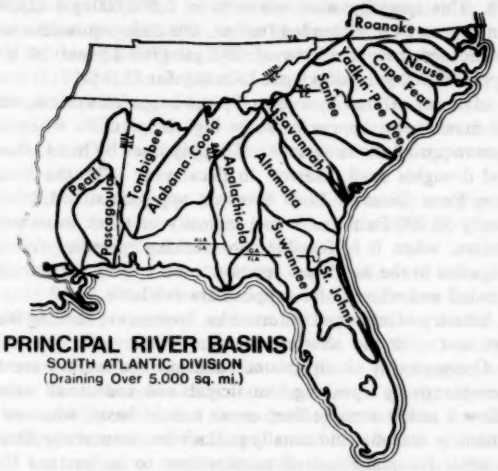

FIG. 2.—Principal River Basins

ground-water withdrawal for municipal, industrial, and agricultural irrigation in limestone aquifers causing ground subsidence in south Georgia and northern Florida; and (d) Tombigbee in Mississippi: pooly productive aquifers could be a limiting factor in further economic development.

3. Water Quality, Fresh-Surface—five major areas cited for fresh-surface water quality problems for various reasons, point and nonpoint sources, include the Yadkin-Pee Dee in North Carolina and South Carolina; Catawba-Broad-Saluda in South Carolina; Lower Chattahoochee and Atlanta Metropolitan area in Georgia; the Coosa in Georgia; and the upper Pearl in Mississippi. (For a map of the principal river basins, see Fig. 2.)

To this point, the cities and areas of concern are but a few of a much longer list given in more detail in the aforementioned report. However, this short list serves as a focal point for further analysis leading to necessary improved

planning and management in these and other important concerns related to water resources of the South Atlantic-Gulf area.

Agricultural Irrigation—Unquantified

The agricultural droughts of 1977 and 1978, which were widespread in the southeast, appear to have prompted an accelerated and dramatic turn to agricultural irrigation. At this point in time, statistics are now becoming available to quantify this expanding demand by location or volume. An example of this expansion can be found in South Carolina, where the acres of irrigated land have doubled each year since 1978. However, as a hypothetical example, a 200-acre (0.809-km^2) tract receiving a total of 6 in. (15 cm) of irrigation (six intervals in one season), converts to 100 acre-ft of water or 33,000,000 gal (125,000 m^3). This quantity also converts to 5,500,000 gal (21,000 m^3) per application in approx 24 h. Extended further, this daily equivalent could provide 27,500 domestic services at a rate of 200 gal (760 L) per 24 h or a single domestic supply of 200 gal (760 L) per 24-h day for 75.3 yr.

Technical advances offered by a central pivot irrigation system, while carrying a high initial investment, appear to solve high labor costs when compared to earlier designs requiring the movement of supply lines by hand labor.

Agricultural droughts spell disaster. In fiscal year 1978, the Small Business Administration Farm Disaster Loan Program approximated 1.8 billion dollars loaned to nearly 50,000 farmers. A vast majority of these loans were drought-related. Farmers, when it is feasible, are seeking remedies for such losses; expanded irrigation in the southeast appears to be a most popular choice, when it can be afforded and when water supplies are available.

Not unlike industry or minicipal waterworks, farmers are seeking water supplies at the lowest cost over the shortest pumping distance in quantities to meet their needs. Consequently, both ground- and surface waters are being used. However, comparatively speaking, municipal and industrial water demands generally follow a rather straight line, on an annual basis, whereas agricultural irrigation demand is seasonal and usually peaks when natural supplies are lowest. It would be wiser for planning and management to understand this vital use of water resources.

Multiple Uses of Resource

Water resources, in general terms of national concept, are no longer a single-purpose resource. Water is perhaps the most versatile of all natural resources adaptable to many beneficial uses for social and economic well-being.

Contrarily, water is a resouce that can, and often is, rendered useless, or nearly so, by poor management practices. This misuse appears in the form of lowered quality which relates to contamination from toxic wastes, excessive evaporation, sediments, and excessive water-oriented vegetative growth, groundwater over-pumpage, salt-water intrusion, poor well design, construction, and management. These are but a few of many hazards leading to a lack of beneficial use at a given time and place.

The past two decades have reflected eras of constant change and technical advances in the planning, construction, and management of water resource

projects. Until the 1970s, it was not unusual to find single-purpose projects, such as those for hydrogeneration or other single purposes. Multipurpose projects as authorized today include benefits for local water supply demands, recreational facilities, and fish and wildlife enhancement except as a natural event.

The multiple-purpose maximum beneficial use concept appears to be emerging as a national policy. The plan for the Upper Savannah Basin developed by the United States Study Commission on Southeast River Basins, published in 1963, detailed a long-range concept for the development of land and water resources to extend to the year 2000 and beyond. Among many multiple uses suggested in this plan, generation of electric energy was one of magnitude. The report details a gross of 804.6 MW being generated by hydropower as of 1960. Of this capacity, 282 MW were being generated at Clark Hill Dam and 330 MW were being generated at the Hartwell Project, then under construction. These capacities reflected most of the power generation in the Savannah Basin upstream from Augusta, Ga., to its headwaters.

Since 1960, on this same reach, hydropower has been added at Keowee (140 MW), Jocassee (610 MW), Russell (under construction with 300-MW hydropower and an additional 300-MW capacity with pump storage operation), for a potential total of 1,350 MW. That's not all—the Duke nuclear generation at Oconee adds another 2,661 MW, requiring about 13 mgd of make-up water for cooling and generation purposes.

Thus, a combined current, or potential electric energy supply, or both, of 4,815 MW is nested between Georgia and South Carolina in a stretch of the Savannah Basin system approx 150 miles long.

Perhaps, and most likely, the team of expert planners who extended the Upper Savannah River plan of development could nor foresee the energy crunch of the late 1970s. The projections made in 1963 assumed an annual load growth rate of about 10%. However, by design or luck, the 19-yr span just elapsed points to some oasis of comfort in that this phase of energy development is near completion at a time quite critical to the national energy dilemma.

It should be carefully noted that these developments have, for the most part, provided excellent recreational facilities, controlled floods, provided low flow limitations (if not augmentation), enhanced the fish and wildlife population, and in some instances, increased the tax base from investments on lands adjacent to reservoirs.

While most of this writer's views on this point are on the plus side of the ledger, there remain several thorny areas not fully reconciled at this time. The question of an assured water supply above project design demands, when not a project purpose, remains a subject for negotiation between the Corps of Engineers and Georgia and South Carolina. Resolution of this issue, expected in early 1981, could enhance future economic and social growth. There is no argument that the water in these reservoirs is a key to the future growth of the region. State growth policies cannot be pursued without access to and use of this tremendous resource for water supply purposes.

New Era for Water Management

The past decade and a half has been dedicated toward numerous national planning efforts in rural and urban settings. Water resources, including both

surface water and groundwater, and the issues of quality and quantity, have not been overlooked even though there remains large data-base gaps in groundwater and less frequently, in surface water.

In the last few years we have seen water policy changes as a national effort under consideration. The present Administration announced this change in the Water Policy Address of 1978. In generating a "new water policy," there has been, perhaps, more confusion than direction which would allow us to move toward resolving water resource problems from a state's point of view, especially in the Southeast. There is absolutely no disagreement with the theory that the states have the first responsibility and should develop and deliver their own water policy. It is true in the western states and, in fact, it is adamant in western states where the doctrine of prior appropriation is the law, as opposed to the riparian doctrine of the states of ths Southeast, East, and Northeast.

In the Southeast, while there is an abundance of water, it is not always well-distributed. It has not been used to its highest potential. There are reasons to believe that if there is economic growth in an economically-depressed area, then one of the most important and greatest attractions will be water for manufacturing, energy, and all purposes, including, but not limited to, a strong defense program for the United States.

This writer is not very impressed, and neither are many state officials, by the so-called "front-end money" to be paid in cash by the states on all Federal projects. An example of the proposed 10% cost-sharing requirements to be required of the states involved in Federal water project construction, is with the Michael B. Russell Project. Georgia and South Carolina were asked to contribute "up front" 10% of the $70,000,000 authorized for pumped storage facilities. In order to gain a sense of consensus, if a state agrees to "front-end money" on its own behalf, then it must be, in most cases, appropriated by the State Legislature. That process is a very hazardous one.

The state has to assure appropriations to match those which could possibly come from the Congress. It is generally true that one legislature cannot bind another. In the whole process, if you can imagine coming to an agreement on a stream common to two states, with two legislatures involved and, later, the Congress as well, it could reasonably take an many as 20 yr to authorize and fund a water project. The hazardous course doesn't stop there. Projects may be challenged in the courts. Further, I can see where the "front-end money process," though these problems, could be very slow. It is a process that could be nonproductive and extremely expensive; in addition, we could spend more money getting to the end target than the target cost itself. This is happening all over our country even now. I think the states have felt, for the most part, that if their investments were to be fruitful, they should have an at least equal if not greater return than the Federal government if we are going to "sell natural resources" on this new kind of market.

Conclusions

The Southeast water supply-demand ratios, I repeat, are good. However, the decades ahead will demand careful management and long-term decision processes on the part of all professionals.

In short, we must train, at our colleges and universities, an expanded number

of geologists and engineers who are intellectually solid in the science and practice of ground-water hydrology. We must bring about a vastly improved system of technology transfer in water-related sciences to local communities. We must improve our methods and technology in well design, location, and construction. We, in the Southeast, must reevaluate our surface water systems to assure that they are not coming under stress—victimized by piecemeal planning.

Importantly, the political climate, in general terms, must be realined with respect to water law. We cannot afford to continue "business as usual." We must seek and support new institutional arrangements within our state boundaries as well as multistate interests.

The states of the southeast region could benefit from formal cooperation, such as was envisioned under P.L. 89-80 with the Title II River Basin Commission and interstate compact agreements. Acting singly, our states are limited in pursuing effective water resource management where states share common water bodies. SEBIAL cannot fulfill this role under its very limited charter. We have an excellent opportunity to do so, since our water resources are not as developed as other areas of country.

The time is now for people in your profession and those in mine to lend a helping hand in developing new horizons where they are needed. Truly, the big job of a growing southland is one of "catch-up," in order to assure a brighter future. There is an important job for each of us if we are willing to do it.

JOURNAL OF
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CITIZEN GROUPS AND ENVIRONMENTAL GOALS[a]

By David S. Froehlich[1]

INTRODUCTION

Engineers working in the areas of water-quality, transportation, or air-quality planning frequently are required to solicit public opinion throughout the course of their work. Despite the importance of citizen participation it is a work element that proves to be a troublesome part of many studies. Frequently the mechanisms that presently are used to elicit public response have failed to generate broad interest in a project. What public input is stimulated is often poorly articulated and not received at a time when it can best affect the course of a study.

Better methods of dealing with the public must be sought if engineers and planners are to continue dealing with large-scale projects that use Federal dollars and affect large numbers of people. One approach that could improve both the quality and usefulness of public input is the greater use of organized citizen groups. The use of such groups in a structured way would overcome a number of problems that now characterize citizen participation efforts.

This paper will outline some the difficulties now encountered with the public-participation aspects of environmental studies, and suggest ways in which these problems may be overcome. If the suggested approach of working with citizen groups proves successful, it will both ease the task of preparing studies and increase their public acceptability.

NEED FOR CITIZEN INPUT

While many professionals yearn for bygone days when engineers were considered experts qualified to establish environmental and social goals, it is clear

[a]Presented at the October 22–26, 1979, ASCE National Convention, held at Atlanta, Ga.

[1]Executive Dir., Wissahickon Valley Watershed Assoc., 12 Morris Rd., Ambler, Pa. 19002.

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that the public has not abdicated its decision-making role in favor of the technicians. On the contrary, the list of technical fields in which citizens are demanding a voice continues to grow. Nuclear energy, despite its highly technical nature, is just the latest addition to the list that already includes such items as water-quality and air-quality planning.

The public can also claim the support of their government. Anyone who doubts that citizen involvement in public sector technical projects is here to stay need only look at the draft of the public participation guidelines for transportation and air-quality planning that were recently published jointly by the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Transportation. The guidelines (2) state the agencies' policy that:

> . . . public participation will continually be provided for, encouraged and assisted to the fullest extent possible . . . . Public information and involvement should begin early and continue throughout the planning process. Responsible agencies should seek and consider the views of a wide spectrum of affected interests.

The document is quite expansive in its definition of the public that is to be included in the decision-making process. It (2) states

> . . . the public is not only the general population but also a collection of constituencies each with varying interests and concerns . . . . As used in the guidelines, public refers to those interests concerned about clean air and likely to be affected by the implementation of transportation control measures. In any given area for any particular measure, these constituencies could include consumer, public health, environmental, civic, neighborhood, minority, labor, trade, commerce and industry, and of course, individual citizens.

It is significant that these guidelines are the joint product of two Federal agencies. Added incentive for taking these guidelines seriously is that grant holders who fail to meet the requirements could have funds cut off within 60 days. It is likely that although these guidelines were formulated for air-quality planning, they are reflective of what EPAs attitude will be toward many other types of environmental work.

Many engineers and planners groan even at the thought of involving citizen groups in the study process; but public participation is a justifiable exercise. When dealing with environmental goals one is working in an area that by its very nature will affect the surroundings in which people live. One is dealing with health and quality of life; surely the affected persons should have a say in what is being produced.

Anyone who has been through a 201 or 208 water-quality study has an extensive repertoire of citizen-participation horror stories. However, these same planning efforts have also produced successes that came about largely because of citizen involvement. In Philadelphia the depth and seriousness of the consideration given to land treatment of sewage was the result of agricultural, open space, and environmental groups' pressure on the 208 study consultants and lead agency. Although the plan was billed as primarily a water-quality effort, open space

and environmental groups viewed land treatment as not only a sensible way to deal with sewage, but also as a way to meet non-water-quality objectives such as preservation of open space and maintenance of ground-water levels. Early resistance by the engineers was eventually overcome and it turned out that land treatment was, in fact, the most appropriate option in some cases (1). This same pressure was felt in other parts of the country as well with much the same results (3).

Highway design has produced some of the most bitter confrontations between citizens and technicians. The country has undoubtedly paid a price for this participation in the form of delayed and more expensive construction. Yet, some good things have come out of the struggles as well. Again Philadelphia provides an example. Those traveling route I-95 through that city will notice that a portion of the highway is not only below grade level, but is enclosed. The highway actually has a roof on it and on the roof is a park that links one of the city's loveliest, but formerly most rundown sections to a renewal project along the waterfront. An interstate highway with a park on it is not an option road designers normally put into their cost-benefit analysis. In this case, however, the enclosure option was considered and constructed following strong local pressure toward that end. What is more, the project has had strong positive effects both in the form of recreational benefits and in the impact it has had on the revitalization of Philadelphia's historical district. Again, it represents an instance of the setting of multiple objectives as a result of local involvement. It is the type of decision-making which, after the pain of confrontation has disappeared, will undoubtedly be viewed as foresighted and beneficial.

Role of Citizen Organizations

One technique for overcoming some of the problems of dealing with the public is the increased use of citizen groups—organizations of people who on their own have banded together to achieve some goal. These groups generally focus on such areas as environmental protection or neighborhood improvement. They have a governing body such as a board of directors, often are incorporated, and communicate regularly with their members. Some, but not all are tax-exempt organizations. Civic associations, watershed associations, and historical societies are examples of such groups. Excluded from the definition of citizen organization as used in this paper are bodies organized by public agencies or their consultants specifically to assist in a study.

If properly selected so as to be capable of performing the tasks desired, citizen groups can be a boon to planning efforts. Certainly they exist in abundance. They represent a broad spectrum of interests. In addition, many groups employ staff persons with technical backgrounds who are capable of understanding complicated subjects and articulating issues to their members and to study consultants.

So, the question is not whether citizen participation is valid (it is) or necessary (it is mandated for many projects). The question is how can the process be done better with greater participation and with less acrimony. Certainly citizen participation often has not been done very well in the past. Too many planners and engineers frequently attend public meetings at which staff attendance exceeds the attendance by the public. In addition, those working on public sector projects

are painfully aware of the "wait-until-the-end" syndrome where no one shows up until the last meeting at which time people surface from everywhere to explain where the study went wrong. These same individuals usually spend half the meeting asking for explanations of issues which were routinely covered in public forums during the preceding two years. Finally, they become exercised about the consultant's refusal to listen to and work with public comments. These are symptoms of a communication failure.

It is probably in the area of communication that most citizen groups will be the most effective. Almost all such organizations whether a civic association, a watershed association, the League of Women Voters, or a large national group such as the Sierra Club, regularly communicate with their membership, usually through a newsletter. The people who read these publications are generally knowledgable and interested in the areas in which the groups specialize. Members of environmental groups, not surprisingly, are concerned about water, wildlife, and the preservation of natural resources. Hunters too are knowledgable about open space and preservation. The League of Women Voters tries to keep its members informed about a broad array of topics.

One of the biggest advantages of communicating with citizens through the newsletters of the organizations to which they belong is they are likely to view the material presented in a more positive light than they would if it came from other sources such as a newsletter prepared just for the study. In most cases group members have contributed money to the organizations. They do this because they believe in what the group is doing or what it stands for. But most importantly, they approach the group with a feeling of trust. Anyone who communicates with people through the newsletter of their favorite group is bound to benefit from the trust and positiveness people feel for their favorite cause.

Secondly, technicians trying to establish environmental and social objectives can address a far larger audience in a meaningful way than they can through the standard public-participation channels. Most groups that an agency would be working through have memberships that range from several hundred to several thousand people. The likelihood that these people will read and retain what is in their organizational newsletter is far greater than it is that they will read a press release printed in the local newspaper. Also, the likelihood of someone reading a newsletter is much greater than the probability of getting him to attend a meeting.

The hosting and organizing of public meetings is, however, another area where citizen organizations can be an effective adjunct to a public-participation program. Many of the same factors of trust, attentiveness, and the ability to address large numbers are relevant here too. Citizen groups need not be restricted to meetings involving only their members, although they probably communicate best with their supporters. If the group that the study consultant or agency is working with has been properly selected, there will probably be some spillover of goodwill to the public at large. Again, this ought to produce better communication than exists between the public and an engineering consultant or a government.

Communication should not be one directional. Most citizen groups will not tolerate merely being a conduit for the dissemination of official information. If one envisions that as the group's primary role, the effort will probably break down during the study. By that time, the organization will undoubtedly have formed opinions of its own about how the plan should be done and there must

be an outlet for these views. In addition, if local groups are not asked to formulate opinions, a great resource is being wasted.

In order to meet the mandates of true citizen participation, to keep citizen groups in the mainstream of the study process, and one hopes not working against the plan, and to get a coordinated response from a large number of people, groups should be asked to identify important issues for the study and to suggest objectives. The way in which this is done is of utmost importance. Procedures for establishing consensus must be explicit and understood by both the study consultant and the citizen organization. Background reports, a series of workshops, a poll of the membership, and the establishment of special committees are all possible approaches. The two things which must not be lost sight of are that there must be a tangible end product such as a list of issues or a set of proposed objectives and that the end product should, as much as possible, actually represent the membership. It cannot merely be the opinion of the executive director or the organization's president. If this happens, one may have coopted the organization, but one has not achieved citizen input, which, after all, is the objective.

If the preceding conditions are met, and a variety of citizen groups have been involved, then several important things will have been achieved: (1) There will have been the involvement of far more people than normally is the case; (2) there will have been meaningful *two-way* communication with these people; (3) groups of people will be better informed about the pertinent issues than they would have been otherwise (just the participation in the objective-setting effort will mean that some of those involved will have read and thought about the subject fairly extensively); (4) numerous individuals will be woven into the study process early in the game, an effort which one hopes will reduce the number of people suffering from the end-of-the-study syndrome; (5) perhaps most importantly, the study consultant will have a concrete statement of the position of the groups involved. This is a rarity for most planning efforts. More commonly, one has only the minutes of a rambling and disjointed discussion at a public meeting. Decisions or well-articulated statements at such events are not the rule. Inevitably, there will be conflicts among the object sets proposed by the various groups, but at least the clear statements can be a starting point in the efforts to resolve differences.

The last role which should be considered for some citizen groups is involvement in the preparation of the technical plan itself. Of necessity, this would be a limited participation. Nevertheless, it could sometimes be very helpful. As was noted earlier, many citizen organizations have a small staff of professionals who are technically competent in some fields. Citizen groups also often have access to real expertise among their membership. They frequently have data which are not available elsewhere and they usually have very good local contacts. If used properly, these attributes can be an asset to the study. In addition, it involves the group in the study, thereby generating within the organization a feeling of being associated with the project. This involvement may help to keep the group in the camp of the study's supporters during the course of the project.

In the past, most citizen organizations have enjoyed a favored status. They have been invited to attend public meetings, respond to questionnaires, and make comments. They have considered it their right to do these things. But

they have been afforded opportunity without the obligation to be thorough, rigorous, and complete. More stringent demands must be made of these groups. They should be asked to perform specific tasks and the study consultants or public agencies should demand results. Obviously, this is a markedly different kind of relationship with these groups than has existed before, and it demands a different kind of institutional arrangement as well.

Essentially citizen groups should be treated as consultants. The organizations selected to perform certain tasks, whether organizing meetings, holding workshops, polling their members, or identifying issues, should be hired for their work. They should have a contract, a work program, a description of tasks, and they should be paid. The groups must be paid because only then can the engineer or public agency require the citizen organization to produce the kind and quality of information that is necessary for the study. While the product delivered under this consultant arrangement should be superior to that of the normal citizen participation process, the expense to the agency need not be great. Most citizen groups would be eager to participate in the setting of environmental objectives or in other parts of a major study. In addition, the vast majority of organizations, whether nonprofit or not, have a constant struggle for money and even small amounts of income to offset the cost of their participation are often meaningful.

This arrangement may have legal and tax implications for the groups. However, these can only be evaluated on a case-by-case basis. Factors to be evaluated include: whether the income would be considered "related" or "unrelated" in the eyes of the Internal Revenue Service, and the amount of money involved. In some cases, an agreement which calls only for the reimbursement of the group's costs may be the most appropriate.

Caveats

Technicians who intend to use citizen organizations in their studies should be aware of several caveats.

1. Group selection is critical to the success of the effort. One must choose groups whose interests are relevant to the topic of the study. They should be fairly impartial and representative of their members. Most importantly, the citizens organization should be well run, have a knowledgable staff or corps or volunteers, and be capable of performing the task asked of them. Selecting the proper groups will be a very difficult job.
2. It is important to structure the study so that it is relevant to people. This applies not only to subject matter, but geographically as well. Individuals relate to relatively small areas, their streets, their neighborhoods, and sometimes, their municipalities. Almost nobody identifies with a metropolitan area in a way which is useful for most studies. If one must deal in large-scale problems, phrase the issues in fairly local terms and try to generalize from the answers.
3. Be explicit about what is really up for grabs. Do not ask groups to take a position on issues they cannot affect. If certain objectives have been established legislatively, this should be clear. In addition, groups should understand and frequently be reminded of their true role in the decision-making process. Most citizen groups will never be more than advisory and they must know who really

will be deciding issues and selecting objectives.

4. If you ask questions, be prepared to listen to the answer and act on it positively. If you ask a citizen group if they wish their town to remain open, green, and sylvan forever, planners and engineers better know what action to take if the answer comes back "yes." The answer must be taken seriously.

5. Similarly, those working with citizens organizations must be prepared to accept suggestions from the groups on how some parts of the study should be run. A certain amount of flexibility will be very helpful.

6. One should remember that working with organizations in the ways discussed above is a supplement, not a substitute for the more traditional public-participation mechanisms. Citizen groups will provide useful information, but they are not a panacea for the problems of dealing with people.

Conclusions

Citizen organizations are a valuable resource that can be used effectively to gather information and help establish environmental objectives. By using these organizations as consultants, engineers can better meet both the moral requirements for public participation and the standards established by government agencies. However, the groups must be assigned specific tasks and have an understanding of exactly how the task should be accomplished.

Working with citizen groups as consultants is an approach which will require experience and practice to reach peak effectiveness. However, if used in a manner which is sensitive to both the needs of the study and the citizen group, the system shows promise for improving the quality of many environmental studies.

Appendix.—References

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JOURNAL OF THE WATER RESOURCES PLANNING AND MANAGEMENT DIVISION

LAKE MICHIGAN DIVERSION FOR WATER QUALITY CONTROL

By James W. Male,[1] A. M. ASCE and Karim Soliman[2]

INTRODUCTION: THE CHICAGO RIVER AND CANAL SYSTEM

The water resources of the nation often are called upon to serve several purposes, not all of which are compatible. The problems that arise when conflicting demands are placed on a body of water are often greatly compounded when the physical characteristics of the waterway are altered by man to meet new demands.

The Chicago River and Canal System is an example of a natural waterway that has been modified in order to serve several purposes. The system is managed to provide a receptacle for treated wastewater, assure a navigable waterway, and control flooding, while maintaining a quality of water consistent with public health and esthetic considerations. Design of the system permits significant control over the allocation of flow to its various tributary channels. Nevertheless, simultaneous satisfaction of the requirements of each type of use coupled with severe legal restrictions on the diversion of Lake Michigan Water Necessitates judicious management of the system.

The intent of this paper is to present a mathematical programming procedure that can aid in the management of the River and Canal System by determining the average monthly diversion rates at each of three diversion points on Lake Michigan. The objective of the procedure is to determine the minimum amount of water diverted directly from Lake Michigan necessary to maintain water quality standards in the River and Canal System. The procedure involves formulating the problem as a flow network which can be easily solved by either an efficient network procedure or its equivalent, discrete dynamic programming.

[1]Assoc. Prof., Dept. of Civ. Engrg., Univ. of Massachusetts, Amherst, Mass. 01003.
[2]Project Mech. Engr., Flour Power Services, Inc., Chicago, Ill. 60606.

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Formulation of the procedure involves several restrictive assumptions; therefore the best use of the methodology is as a screening procedure.

In order to acquaint the reader with the River and Canal System a brief description of the physical setting, regulations, and current operation follows.

Physical Setting.—The Chicago River and Canal System is a unique network which has undergone gradual development to meet various needs of the greater Chicago metropolitan area. Fig. 1 shows the configuration of the waterway, which consists of natural streams and man-made canals. Construction of the

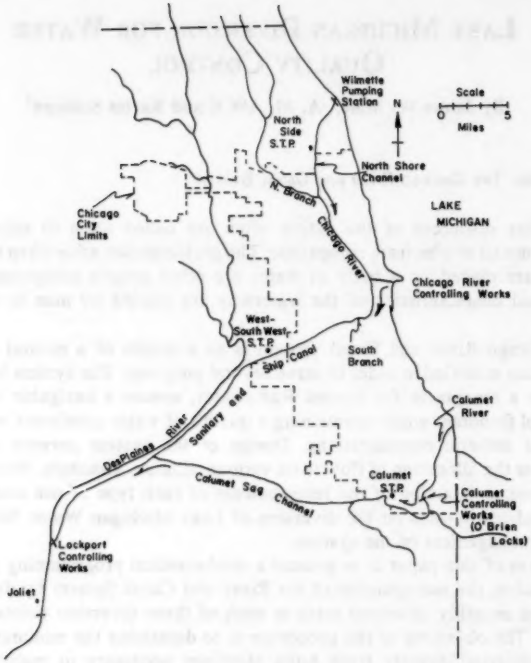

FIG. 1.—Map of Chicago River and Canal System

canals in the early part of this century resulted in a flow reversal in two of the rivers. Water currently enters the River and Canal System from Lake Michigan at three points—Wilmette Pumping Station, Chicago River Controlling Works, and Calumet River Controlling Works (O'Brien Locks)—and empties into the Des Plaines River where flow is regulated by the Lockport Controlling Works.

Water flowing through the three diversion points is termed direct diversion, and is attributed to: (1) Leakage at the three diversions; (2) lockage at the Chicago River and O'Brien Locks; (3) a small amount of navigational makeup water; and (4) dilution water added to help maintain water quality. The lockage,

leakage, and navigational makeup water are considered fixed and termed nondiscretionary, while the dilution water is considered discretionary. Both discretionary and nondiscretionary diversions provide relatively good quality dilution water, but only the discretionary portion can be varied in response to prevailing water quality conditions.

In addition to discretionary and nondiscretionary diversions at the three controlling works, the system also receives storm water runoff diverted from the Lake Michigan watershed, and ultimately receives water drawn from the Lake for Chicago's municipal water supply. The total diversion is thus the sum of direct diversions, municipal water supply, and stormwater runoff diverted from the Lake Michigan watershed.

Three major sewage treatment plants contribute effluent to the River and Canal System. Although the flows are large (350 MGD = 15.3 m^3/s, 870 MGD = 38.1 m^3/s, 210 MGD = 9.2 m^3/s), they achieve on the order of 85% to 98% BOD removal. Nevertheless, Chicago has a combined sewer system, and when large storms occur the treatment plants are bypassed and effluent is discharged directly to the system after chlorination. Such intermittent loadings contribute greatly to the generally poor water quality of the River and Canal System in two ways: (1) By oxygen depletion due to the high concentration of BOD in the wastes; but more importantly (2) through the resulting benthic deposits which continue to deplete oxygen after the discharge of wastes. Dissolved oxygen levels are often substandard and during summer months some sections of the waterways system become anaerobic.

Some construction projects have been proposed for the waterway which should improve the quality of water in the River and Canal System. The project with the most immediate impact will be the installation of 10 instream aeration stations located at critical areas within the system. Each of the diffused air stations is expected to raise local DO levels to within 90% of saturation concentration (16).

Regulations.—Several statutes govern the operation of the Chicago River and Canal System. These include the maintenance of water quality standards and a restriction on water diverted from Lake Michigan.

The 1973 Water Pollution Regulations of the Illinois Pollution Control Board (10) specify several different water quality standards for the River and Canal System as a whole. This paper will consider DO (dissolved oxygen) levels, which will be specified in a later section.

The U.S. Supreme Court ruled that as of March 1, 1970 the State of Illinois would be restricted to a total annual average diversion from the Lake Michigan Watershed of 3,200 cfs (89.6 m^3/s) (21). The ruling allows the use of a five-year accounting period but restricts average flow to no more than 3,520 cfs (98.6 m^3/s) in any one year. However, passage of the Federal Water Resources Development Act of 1976 included a provision allowing Illinois to divert up to 10,000 cfs (280 m^3/s). The Act, which allows a trial five-year period, permits this diversion only when lake levels are above the historical average, and when there is no threat of downstream flooding.

In April, 1977 the Illinois Department of Transportation announced the allocations of water which the State was authorized to divert (9). While 43 of the 196 communities applying for Lake water for municipal use were denied allocations, 320 cfs (9.0 m^3/s) was reserved for discretionary direct diversion.

Current Practice.—Operation of the Chicago River and Canal System is under jurisdiction of the Metropolitan Sanitary District of Greater Chicago (MSDGC). Flow in the waterway is regulated with several considerations in mind, including water quality standards, federally imposed flow regulations, and requirements of flood control and navigation. Navigation standards of the U.S. Army Corps of Engineers require that water levels be maintained within a specified range. Based only on diversions and natural flow (neglecting storm runoff), water levels are maintained as high as the navigation and streamflow regulations will permit in order to maximize the total dissolved oxygen in the system. Since streamflow regulations are specified on an annual basis, determination of reasonable monthly flow rates has become somewhat of an art, based largely on operating experience gained since implementation of the regulations.

TABLE 1.—Lake Michigan Diversions by Illinois*

Type of diversion (1)	Amount of Water Diverted, in cubic feet per second					
	1971 (2)	1972 (3)	1973 (4)	1974 (5)	1975 (6)	1976 (7)
Direct diversion	726	1,322	958	640	541	475
Storm runoff	679	157	857	774	888	977
Domestic supply	1,677	1,675	1,652	1,699	1,670	1,658
Total	3,082	3,154	3,467	3,113	3,099	3,110

*Source: The Metropolitan Sanitary District of Greater Chicago, Maintenance and Operation Annual Report (19,20)

Note: 1 cfs = 0.028 m^3/s.

Values for the three major categories of diversions for the years 1971 through 1976 are shown in Table 1.

Problem Statement

The constraints on the volume of water which the State of Illinois may take from the Lake Michigan watershed apply to direct diversions, diverted runoff, and water drawn for municipal use. (The total amount applies essentially to the Chicago area where water is diverted from the Lake Michigan watershed. Since the withdrawals of other Illinois municipalities are eventually returned to the Lake, they are not included in the balance.) Projected requirements are high because of a continually increasing demand in Chicago and many surrounding communities for municipal water, and because of direct diversions required to maintain water quality standards in the River and Canal System.

Dissolved oxygen levels in the system are often below standard and some sections become anaerobic during summer months. Judicious allocation of Lake water available for diversion, combined with the expected performance of instream aeration units, should enable maintenance of the DO standard. Nevertheless, any Lake water used for dilution purposes reduces the amount of water which would otherwise be available for municipal requirements.

Of the several means by which Lake water is added to the system (direct

diversion, treated municipal effluent, stormwater runoff), the direct diversions are most amenable to control and to better management. Since the amount available for domestic use increases by the amount which can be pared from use for direct diversion, there is a strong incentive to develop a protocol for efficient management of direct diversions. The remainder of this paper describes an optimization procedure which determines the minimum direct diversion necessary to maintain dissolved oxygen standards in the system, and which allocates the diversion both temporally and geographically, allowing a decision maker to specify the monthly average diversion at each of three diversion points.

Mathematically, the problem can be expressed as

$$\text{Minimize} \sum_{i=1}^{3} \sum_{j=1}^{12} q_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

subject to

$$f_k\left(\sum_i q_{ij}\right) \leq \text{SATDO}_j - \text{DOSTD}_k \quad \text{for} \quad j = 1 \ldots 12 \quad \text{and} \quad k = 1 \ldots 11 \qquad (2)$$

in which q_{ij} = average inflow at diversion point i during month j; SATDO_j = saturation dissolved oxygen during month j; DOSTD_k = dissolved oxygen standard for reach k; and $f_k(\Sigma_i q_{ij})$ = function to determine the dissolved oxygen deficit in reach k. (The limits of the summation depend on the diversion affecting the DO concentration. These will be detailed further.)

Related Research

Several researchers have applied optimization procedures to characteristics of the dissolved oxygen sag curve to aid in water quality management decision making (1,6,7,13,18,24,25,27,29). In most of these studies flowrate was known and assumed constant, and management decisions were reflected in waste discharge allocations. Optimization procedures have also been applied to the effects of low flow augmentation on dissolved oxygen concentrations (14,26,30).

The Chicago River and Canal System has been the subject of several studies concerned with specific indicators of water quality and with the over-all effects of the system on water use in Northeastern Illinois. Specific aspects of water quality prediction and of factors that determine water quality have been the subject of several reports by the Illinois State Water Survey (2,3,4,5). In research conducted by MSDGC (15,16) a simulation procedure was used to calculate the discretionary diversions which would be required on dry weather days for various future scenarios. A similar study was performed by Harza Engineering Company (8) using QUAL-II (22) as a basis for calculations. Keifer and Associates (11) determined potential reductions in the use of dilution water as part of an over-all study of water needs in Northeastern Illinois.

Solution Procedure

The procedure developed in this section solves the problem stated in Eqs. 1 and 2 by solving 12 separate optimization problems using monthly average conditions for each. As a result, the procedure determines the minimum monthly

diversions necessary for maintenance of water quality standards. Formulation of the solution procedure involves: (1) Division of the waterways network into four sections; (2) determination of the relationship between flowrate and dissolved oxygen for each section; and (3) a representation of possible dissolved oxygen concentrations and flowrates in a network structure. An efficient network optimization procedure is then used to determine minimum diversions for each month. These steps are detailed in the subsections, which follow.

Sectioning the Waterway System.—To model the waterway, the River and Canal System was divided into four sections and each section subdivided into

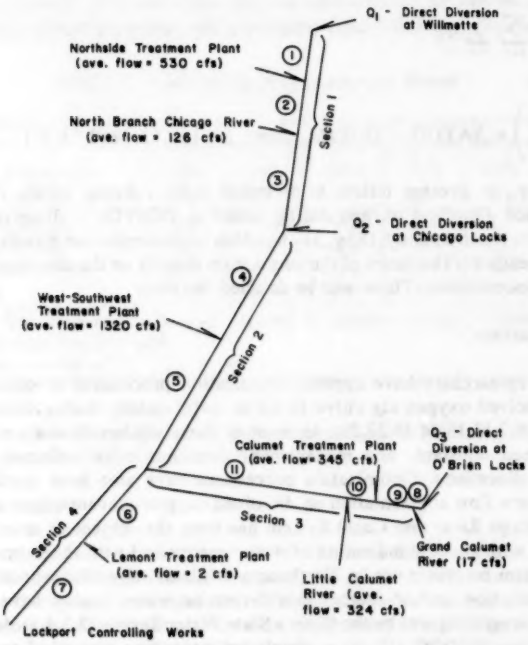

FIG. 2.—Schematic Diagram of River and Canal System (Note: 1 cfs = 0.028 m^3/s)

reaches. Locations of the 11 reaches so designated are shown in Fig. 2. A small segment at the mouth of the Chicago River was ignored in the sectioning, and the inflow at the Chicago River Controlling Works was assumed to be at the junction of the North and South branches. In Fig. 2, the average flowrates shown are those for 1973; circled numbers represent reach numbers.

Specification of the four sections and 11 reaches allows a more detailed statement of Eqs. 2. These can now be written

$$f_k(q_{1j}) \leq \text{SATDO}_j - \text{DOSTD}_k \quad \text{for} \quad j = 1 \ldots 12 \quad \text{and} \quad k = 1, 2, 3 \quad \ldots\ldots (3)$$

$$f_k(q_{1j} + q_{2j}) \leq \text{SATDO}_j - \text{DOSTD}_k \quad \text{for} \quad j = 1 \ldots 12 \quad \text{and} \quad k = 4, 5 \quad \ldots (4)$$

$$f_k(q_{1j} + q_{2j} + q_{3j}) \leq \text{SATDO}_j - \text{DOSTD}_k \quad \text{for} \quad j = 1 \ldots 12$$

$$\text{and} \quad k = 6, 7 \quad \ldots (5)$$

$$\text{and} \quad f_k(q_{3j}) \leq \text{SATDO}_j - \text{DOSTD}_k \quad \text{for} \quad j = 1 \ldots 12$$

$$\text{and} \quad k = 8, 9, 10, 11 \quad \ldots (6)$$

For simplicity's sake the subscript j will be dropped for the remainder of the paper since the solution procedure is the same for each month. Therefore, Q_i will refer to the diversion flowrate at location i for any month in general.

Dissolved oxygen concentrations in the reaches of the waterway system are calculated on the basis of the Streeter-Phelps equation (28) as

$$D_t = \frac{K_1 L_0}{K_2 - K_1}(e^{-K_1 t} - e^{-K_2 t}) + D_0(e^{-K_2 t}) \quad \ldots (7)$$

in which D_t = dissolved oxygen deficit at time t; K_1 = coefficient of deoxygenation; K_2 = coefficient of reaeration; L_0 = concentration of organic matter at $t = 0$; and t = time of travel. No specific term is incorporated to account for the sludge oxygen demand (SOD) present in certain sections of the River and Canal System. Instead, SOD is incorporated into the deoxygenation rate constant K_1, using a procedure suggested by Butts (2) for determining the values of K_1.

The DO profile for each section is made up of individual profiles for the reaches comprising the section. Each reach is assumed to be completely mixed and initial conditions are calculated by mass balance. Average monthly temperature, BOD and DO concentrations of the Lake water at each diversion point are used as characteristic of the influent water. Tributary inflow and wastewater treatment plant effluent characteristics (flow, temperature, BOD, and DO) are assumed constant and equal to the monthly average.

For each monthly period, the only variable inputs affecting DO concentration are Q_1, Q_2, and Q_3, the diversion rates at the head of Sections 1, 2, and 3. The resulting DO concentrations then will depend on the flowrate into the head of each section. To avoid confusion, the term flowrate will refer to the actual flow in a stream section, while diversion flowrate will refer to that part of the flow which was diverted directly from the Lake. While the flowrate in each section will depend upon a particular set of factors, it will nevertheless be a function of one or more diversions plus a sum of constant (average monthly) tributary inflows.

Altering diversion will change the flowrates in the appropriate sections, and will affect the DO profile by either raising the DO concentrations for a high flowrate (more dilution water), or the reverse. The relationship of DO profile to flowrate is shown in Fig. 3(*a*). The effects of five possible diversions are shown, in this case each with the same DO, temperature, and BOD conditions at the beginning of the section. Each possible diversion results in a different DO curve and therefore different critical and outlet values of DO concentration.

There are three possible outcomes resulting from different flowrates. First, DO concentrations at the end of the section and at all points in between are greater than the minimum DO standard. Second, the DO concentration at the

end of the section is in violation of the DO standard; and third, the final DO concentration meets the DO standard, while the critical deficit occurs before the end and violates the standard. The first case is shown by the upper three curves in Fig. 3(*a*). The second and third cases are shown by the curves labeled 20 cfs and 40 cfs (0.6 m^3/s and 1.2 m^3/s), respectively.

Formulation of Network Structure.—The network developed in this section consists of nodes representing the DO concentration at the end of each stream section, and arcs representing the appropriate diversion value which results in that concentration. Fig. 3(*b*) presents that portion of the network which corresponds to the DO curves depicted in Fig. 3(*a*). Node 18 in Fig. 3(*b*) represents

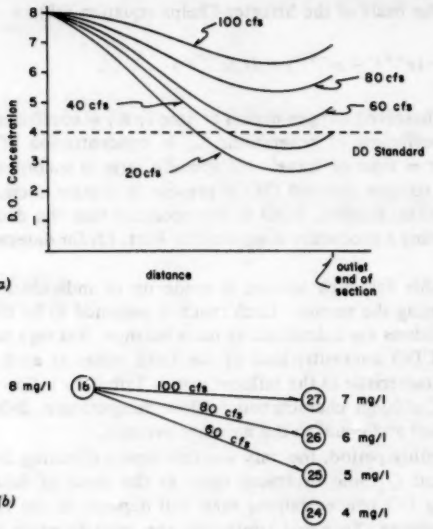

FIG. 3.—Conversion from Graphic to Network Representation: (*a*) Dissolved Oxygen Profiles; (*b*) Network Representation (Note: 1 cfs = 0.028 m^3/s)

a discrete DO concentration at the beginning of a section of the waterway system. Nodes 24, 25, 26, and 27 represent discrete DO concentrations at the end of the section resulting from specific diversion values at the beginning of the section. A diversion rate (in cubic feet per second) is used to identify each arc connecting node 18 with its corresponding resultant node. Arcs are not included for the 20 cfs and 40 cfs cases, since they violate the DO standard and therefore do not satisfy the constraints of the problem.

The exit DO concentrations in the network are calculated with the Streeter-Phelps equation. For an assumed initial DO concentration (left node) and known parameters (temperature, BOD input and flowrate from tributaries, treatment plants, and upstream reaches), the total flow (including a diversion flowrate)

is used to calculate the DO concentration at the end of the reach (one of the right nodes).

This process may be repeated for different discrete values of initial DO (different initial nodes) to determine DO concentrations resulting from different diversions. Thus, a range of possible DO concentrations (nodes in the network) at both the beginning and end of each section may be examined. Initial concentrations depend upon circumstances above the section in question. A final concentration depends upon the initial concentration (node at the beginning of the section) and the flowrate through the section. The flowrate is in turn the sum of the flow from the upstream section(s), tributary and treatment plant inflow, and diversion into the section (the value of the arc in the network). This expanded network is illustrated in Fig. 4, in which the first column of nodes represents possible DO concentrations at the beginning of a section, and the second column represents possible resulting DO concentrations.

In Fig. 4 temperature and BOD mass are assumed constant at the beginning of each section, for each monthly application of the model. This assumption is reasonable since each varies only slightly for different diversion rates. The

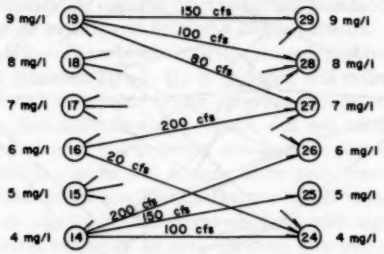

FIG. 4.—Network Structure for One Section (Note: 1 cfs = 0.028 m^3/s)

flowrate, however, has a greater effect. Because of the configuration of the problem at hand, the influence of flowrate may be easily incorporated into the network structure and will be described further as the entire network is developed. The over-all network is constructed using the network sections as described previously; therefore, the network in Fig. 4 will be "repeated" for each section.

Fig. 5 illustrates the entire network, for which there are three segments corresponding to river sections 1, 2, and 4. The segments are delineated by columns of nodes, with only one node in the first and last "columns." Each column represents a range of possible discrete DO concentrations with values chosen to emphasize the lower concentrations. The DO concentrations were altered by increments of 0.1 mg/L between concentrations of 4.0 mg/L and 4.9 mg/L, 0.2 mg/L between DO concentrations of 5.0 mg/L and 7.0 mg/L, and 0.5 mg/L between DO concentrations of 7.0 mg/L and 11.0 mg/L. Each node, therefore, represents a small range of DO concentrations. For example, an actual DO concentration between 5.0 mg/L and 5.3 mg/L is represented in the network by a single node having a DO concentration of 5.2 mg/L.

As can be seen from Fig. 5, the node at the end of one segment becomes the initial node for the next segment. The DO concentration at the end of one section cannot be used as the initial DO concentration for the next section, however, without making adjustments which depend upon the characteristics of the diversion at the beginning of the downstream section. One of these characteristics is the value of the diversion itself. With the diversion rate known, a mass balance on dissolved oxygen may be used to determine initial conditions for the next section. Following this determination, the exit DO may be calculated as before.

For a given month, an average DO concentration is assumed at the beginning of Section 1, the Wilmette Pumping Station. This is represented by the single

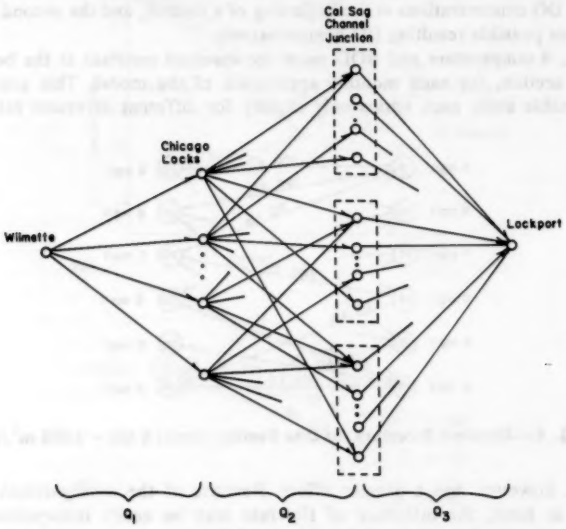

FIG. 5.—Network Representation of Flow Alternatives with Nodes Representing Dissolved Oxygen Concentrations

node of the first column of Fig. 5. At the end of the first section, each DO concentration obtained is associated with a particular diversion from the Wilmette Pumping Station and is assigned a node representing its final DO concentration. The group of nodes at this point make up the second column in the network. Each node represents a DO concentration and total flow up to that point in the waterway.

The value of the arc connecting Node 1 to any particular node in the second column is equal to the diversion required from the Wilmette Pumping Station to obtain the DO concentration represented by this particular node at the end of the first section.

Depiction of the second column of nodes is straightforward because the flow

and calculated DO are based only upon an initial DO and diversion rate at Wilmette. The third column requires a more complex structure, however, because the several values of DO at the end of the second section can result from different combinations of diversions at Wilmette (Q_1) and the Chicago River (Q_2). Since the total flow at this point has an impact on the downstream (Section 4) DO concentration, its value must be contained in the nodes. This is done by dividing the third column of nodes into three subgroups, each representing a range of possible flows. The ranges are determined by using the expected minimum and maximum flowrates at this point and dividing the column into three ranges. As a consequence, each node represents both a small range of DO concentrations and (depending upon its respective subgroup) a range of flowrates.

The last column in the network contains one node representing the minimum allowable DO concentration at the Lockport Controlling Works. The diversion value placed on the arcs leading to the last node is that from the O'Brien Locks, Q_3. This use of Q_3 allows us to ignore Section 3 in the construction of the network, because any diversion at the O'Brien Locks must satisfy the DO standard in that section before it is considered in the computations for Section 4. The minimum Q_3 capable of maintaining standards in both sections is used as the value on each arc in Section 4 of the network.

Use of the Network.—The objective of the stated problem is to determine the minimum total diversion ($Q_1 + Q_2 + Q_3$) that will maintain water quality standards. The network developed in the previous section contains arcs representing only those diversion flowrates which will not violate the standards. Due to the configuration of the network, any path (a sequence of arcs) from the first node to the last node will include three arcs, one representing each of the three direct lake diversions. This characteristic will be exploited by utilizing an efficient network algorithm, called the shortest path algorithm, which will determine the shortest sequence of arcs between any two specified nodes in a network. Several shortest path algorithms are available, exhibiting slightly different characteristics and capabilities. Pierce (23) provides a comprehensive bibliography of various shortest path algorithms.

Once the network is completed, the shortest path algorithm is applied to find the sequence of arcs whose sum ($Q_1 + Q_2 + Q_3$) is smallest. The diversion flowrates associated with the first, second, and third arcs in the minimum sequence represent the respective diversions at Wilmette, and the Chicago and Calumet Rivers.

The procedure is the same as discrete dynamic programming where the state variables are DO concentrations and flowrate, and the stages are the three sections of the network. Liebman and Lynn (13) and Meier and Beightler (18) used dynamic programming to solve similar water quality problems. In these cases, however, the flowrate was assumed constant and treatment plant efficiencies were variable.

The number of feasible arcs generated between each node column depends upon the number of diversions tested at each diversion point and the number of diversions which result in feasible DO concentrations. To minimize the number of diversions tested, an iterative procedure was used (17). The procedure chose a wide range of a few diversion values and solved the optimization in order to narrow the appropriate range for the second iteration. Experience with the

iterative procedure revealed that, in general, three iterations were necessary to narrow the tested diversion values to increments of 5 cfs (0.1 m^3/s).

The procedure has thus far been described using average monthly input data. To determine variations from month to month the algorithm must be solved for each month. This requires three iterations for each month, for a total of 36 applications of the algorithm.

Results

The optimization procedure was coded in Fortran IV and run on a CDC Cyber 74-18. Average CPU time for one iteration of all 12 months was approximately 6 sec. Computer size limitations restricted the size of the network to 160 nodes.

Two cases were analyzed: (1) Conditions currently existing in the study area; and (2) conditions expected to exist following installation of the 10 instream aeration stations.

Average monthly flow rates for tributary and treatment plant inflows were used as inputs to the model. Their use was based on the fact that the desired monthly diversion rates are also monthly averages. Adjustment of the diversion rates during a month should reflect existing conditions in the appropriate stream section. In the past, the adjustment has primarily reflected navigation and flood control; however, a decision should also be influenced by both water quality and the allotted average monthly diversion. Water quality could be predicted for very short time horizons based on considerations such as tributary flowrate, quality, and temperature. The average diversion should be used as a target value much as the total diversion value of 3200 cfs (89.6 $m^3/$) is currently used as a yearly target.

Existing Conditions.—Current regulations require maintenance of a DO concentration of 4 mg/L for most of the waterway. In addition, the North Shore Channel must be maintained at 5 mg/L for at least 16 hours of the day. To simplify the problem, this value was used for the steady state analysis. The selection of deoxygenation coefficients was made difficult because of the uncertainty of representative rates. Values were chosen based upon data provided by Butts, et al. (4) and based upon calibration of the DO sag curve. The procedure was also run with initial K_1 values increased by 25%. Table 2 shows the results for these two analyses.

In both cases the Calumet Sag Channel requires approximately 72% of the dilution water, while the Chicago River needs very little. The large proportion allotted to the Cal-Sag Channel is due to the high K_1 values and poor quality of influent tributaries. The small portion allotted at the Chicago River Controlling Works is due in some part to the solution technique, since the problem ignores the short section of the Chicago River between the Lake and the junction of the North and South Branches.

In the analyses presented in Table 2, no diversions were allowed below the average existing lockage and leakage values for the three diversion points. The values used correspond to those presented by Keifer and Associates (11). In order to determine what effect lockage and leakage flows have on total diversion the program was run with no lower limit on diversion amounts. The results using the lower K_1 values reveal that the yearly average diversion could be

reduced by approximately 100 cfs (2.8 m^3/s) if all lockage and leakage could be eliminated.

Instream Aeration.—The solution procedure was modified by adding 10 reaches to accommodate the instream aeration stations currently under construction. Three different analyses were made by varying both the deoxygenation coefficient and the aeration efficiency. In all cases lockage and leakage flows are included. Table 3 summarizes the results of the three analyses.

TABLE 2.—Minimum Diversion Under Existing Conditions

Month (1)	Diversion, in cubic feet per second			
	Wilmette (2)	Chicago River (3)	O'Brien Locks (4)	Total (5)
	(*a*) Using lower values for K_1			
January	46	64	85	195
February	46	64	85	195
March	46	135	115	296
April	46	135	275	456
May	46	135	710	891
June	110	157	405	672
July	200	157	500	857
August	220	157	1,025	1,402
September	130	157	2,910	3,197
October	270	92	365	727
November	60	92	76	228
December	46	64	100	210
Average	106	117	554	777
	(*b*) Using higher values for K_1			
January	46	64	100	210
February	46	64	100	210
March	46	140	180	366
April	46	135	310	491
May	90	135	850	1,075
June	190	160	500	850
July	200	157	650	1,007
August	300	157	1,370	1,827
September	200	157	4,450	4,807
October	360	92	450	902
November	115	92	100	307
December	46	64	110	220
Average	140	118	764	1,022

Note: 1 cfs = 0.028 m^3/s.

Possible Extensions.—The solution procedure described herein is based on a steady state analysis using monthly averages. Actual conditions in the River and Canal System are far from steady. Lockage, storm water overflow, and flood control operations result in flows resembling impulse inputs to the system. Diurnal variations in DO concentration also complicate the modeling process. A detailed nonsteady state analysis of the River and Canal System would be

an enormous undertaking. If it were to be done, a straightforward optimization procedure such as that presented herein could be used as a screening procedure to provide starting conditions and average monthly flow "goals" for the simulation.

In most cases an array of "good" solutions is of value to any decision making process. One drawback of the procedure presented is that it provides only the optimal result, but no other feasible, yet close to optimal, solutions. A number of good solutions is of value to decision makers when several considerations must be weighed. Often these considerations cannot be included in a mathematical solution procedure. An example in this case is the desire to reduce flooding by varying diversions.

TABLE 3.—Minimum Total Diversions with Instream Aeration

Month (1)	Diversion, in cubic feet per second		
	Assuming 90% "aeration efficiency" and lower K_1 values (2)	Assuming 70% "aeration efficiency" and lower K_1 values (3)	Assuming 70% "aeration efficiency" and higher K_1 values (4)
January	200	200	210
February	190	190	200
March	293	293	311
April	401	401	431
May	676	681	771
June	548	597	717
July	568	627	757
August	928	1,147	1,467
September	2,383	2,477	3,607
October	252	422	592
November	214	214	228
December	210	210	220
Average	576	621	793

Note: 1 cfs = 0.028 m^3/s.

To allow the presentation of several good solutions to decision makers, a different shortest path algorithm (12) could be used which generates a certain number of paths starting with the best, then the second best, etc.

The results of this study provide the minimum direct diversions necessary to maintain current dissolved oxygen standards. It might be advantageous, however, to divert more than the minimum necessary, an option which is available now that up to 10,000 cfs (280 m^3/s) may be diverted, as authorized by the Water Resources Development Act of 1976. The benefit of higher diversion, of course, would be a higher over-all DO concentration in the waterway. Other factors might also be considered, including: (1) Reduction in the use of instream aerators; (2) increased navigation capability; and (3) increased hydropower generation at Lockport. For these cases, alternative objectives might be to: (1) Maximize the average DO concentration; (2) maximize the minimum DO con-

centration; (3) minimize energy required for instream aeration; or (4) maximize power generation at Lockport.

Summary and Conclusion

An optimization procedure has been presented that is capable of determining the minimum amount of water which must be diverted from Lake Michigan to maintain dissolved oxygen standards in the Chicago River and Canal System. The procedure involves the network representation of possible diversions and utilization of an efficient network algorithm to find the optimal solution. Results of the procedure—temporal and geographical allocation of diversions—are provided for existing conditions and for projected conditions following installation of instream aeration units.

Results of the optimization procedure lead to the following conclusions:

1. Under existing conditions a yearly average direct diversion of from 777 cfs to 1022 cfs (21.8 m^3/s to 28.6 m^3/s) is necessary to maintain the dissolved oxygen standard of the Illinois Water Pollution Regulations. Assuming an average annual value of 256 cfs (7.2 m^3/s) for lockage and leakage, approximately 521 cfs to 766 cfs (14.6 m^3/s to 21.5 m^3/s) should be designated for discretionary diversion.
2. After completion of the instream aeration stations, an annual average direct diversion of from 576 cfs to 793 cfs (16.2 m^3/s to 22.2 m^3/s) will be necessary to maintain the dissolved oxygen standard. This will allow a reduction for discretionary purposes to between 320 cfs and 537 cfs (9.0 m^3/s and 15.0 m^3/s).
3. A large percentage of the direct diversion flow should occur during the months of May through October. Slightly less than half of the total annual flow should be concentrated in August and September.
4. Judicious allocation of the direct discretionary diversion flows among the Wilmette Pumping Station, the Chicago River Controlling Works, and the O'Brien Locks is an important factor in minimizing the necessary diversion.
5. A procedure for continuous adjustment of diverted flows should be developed. The values reported here are average monthly flows. The actual flow at any specific time should depend on existing conditions within the watershed. The procedure should include the objectives of navigation, flood control, and water quality based on available monthly average diversions. Continuous operation should take into account conditions within different geographical areas which may dictate different diversion rates.
6. In light of the Water Resources Development Act, which permits an increase in total diversion in Illinois, procedures should be established for the allotment of water when Lake levels are above normal.

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Appendix II.—Notation

The following symbols are used in this paper:

D = dissolved oxygen deficit;
DOSTD = dissolved oxygen standard;
f = function relating diversion flowrate and dissolved oxygen deficit;
i = subscript, diversion location index;
j = subscript, time period index;
K_1 = coefficient of deoxygenation;
K_2 = coefficient of reaeration;
k = subscript, stream reach index;
L_0 = initial concentration of organic matter;
Q = diversion flowrate;
q = diversion flowrate for a specific month; and
t = time.

JOURNAL OF THE WATER RESOURCES PLANNING AND MANAGEMENT DIVISION

NEW APPROACHES TO WATER UTILITY PLANNING[a]

By Alan K. Rowe[1] and Daniel K. Sander,[2] A. M. ASCE

INTRODUCTION

Public water systems in the state of Washington have two new tools at their disposal to assist them in effective planning for future service. These recent state laws are aimed at making it easier for water utilities to predict future needs and giving them assurance that they will be able to implement their plans. Both laws are thoroughly examined, focusing on the cooperative planning process and the importance of the product: the Coordinated Water System Plan (CWSP).

The types of problems experienced by Washington water systems, which have resulted in the establishment of these two new laws, are also experienced in most urban growth areas throughout the United States. Hopefully, water utilities and planning agencies in other states will benefit from Washington's initiative in creating a responsive planning framework.

BACKGROUND

The state of Washington has an active water supply program administered through its health agency. Its emphasis has traditionally been placed upon two major components: (1) Design review; and (2) monitoring the end product to assure adequate quality.

Responding to increased concern about the environment witnessed in the

[a]Presented at the February 25–28, 1979, ASCE Water Resource Planning and Management Division Specialty Conference, held at Houston, Tex.

[1]Program Mgr., Technical Services Unit, Water Supply and Waste Section, Mail Stop LD-11, Washington State Dept. of Social and Health Services, Olympia, Wash. 98504.

[2]Dist. Engr., Water Supply and Waste Section, Washington State Dept. of Social and Health Services, West 924 Sinto Avenue, L32-4, Spokane, Wash. 99201.

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early 1970s, the state established an entity separate from the Health Department by bringing certain visible, environmentally-oriented programs into the spotlight. Thus, solid wastes, sewage (water pollution), and air pollution were shifted to a new agency, the Department of Ecology. The water resource management program was also transferred into the Department of Ecology from another agency.

The state's drinking water program remained in the health agency primarily because it was commonly associated with protection of public health as differentiated from protection of the environment. This necessitated a close working relationship between the two state agencies—one that has become increasingly positive in recent years, as the need for water planning became more apparent.

Several situations that have taken place in recent years illustrate a need for the water supply program to expand its traditional emphasis on design review and monitoring the end product for adequate quality:

1. Land use planning itself, enjoying revitalization along with the environmental movement, has increasingly occurred without the involvement or support of water purveyors. This has often resulted in conflicts between land use controls and water system expansion, as each responded to different objectives.

For example, a water district was in desperate need of a new reservoir and transmission line. The ideal location was on the hill above the majority of services. This location was especially good since two subdivisions near the selected site had requested service, and the area along the transmission line could be easily served if the line was developed. Plans were finalized before it was discovered that the transmission line went through an area designated by the county as low density. The county objected to construction of the line because it would encourage development.

2. Water purveyors have entered into fierce competition between themselves in attempts to extend their facilities into urban growth areas, using the rationale that these newer, dense areas will increase their revenues. This, in turn, has greatly diminished their ability to predict future, logical service areas, and therefore to carry out efficient utility planning.

Such was the case between a water district and a city in northwestern Washington. Both utilities wanted to serve the area between their systems because of its high development potential. Each utility had anticipated using the same parcel of land on a nearby hill to build reservoirs. Not only would the water tanks be side by side, but dual transmission lines from the reservoirs to the new area to be developed had to be constructed.

3. Many water purveyors, falling victim to the expansionist philosophy, have been tempted to gear their capital investments towards the provision of huge, often unnecessary quantities of an additional source, in order to secure water rights necessary to support water system needs far into the future.

As an example, the State Health Agency has recently been seeking compliance with surface water treatment requirements in a medium-sized city. At the same time, the Department of Ecology encouraged the city to build a new impoundment structure in order to secure water rights. The city, reacting to these conflicting demands for capital improvements, has neither improved its water treatment facilities nor secured additional water rights—thus jeopardizing the integrity of its water system.

These types of situations have brought frustration to water utility managers and agency officials alike. As those responsible for provision of water struggled to deal with these situations, it became essential to articulate a simple goal: to insure that equal or better drinking water will be available to future generations.

Effective water supply planning, together with a recognition of the essential connection between the use of water and the environment from which it is derived would be necessary to accomplish the goal. The goal also calls for a partnership approach: working together with those disciplines affected to achieve a high level of mutual benefits. Addressing a goal such as this in a joint manner leads to support of ensuing programs that in turn increase their chances of success. Coordinated planning for more efficient use of the water resource has indeed become the new direction, or focus, of the Washington State Water Supply Programs.

This new water supply emphasis in Washington has been fully supported by the State Legislature. Two laws and their administrative regulations have provided unique tools to accomplish the water supply program goal: the Water Resource Act of 1971 (WRA), and the Public Water System Coordination Act of 1977 (PWSCA). The remainder of this paper will examine these laws and how they have resulted in a complete, comprehensive relationship between the water resource and the water user.

PWSCA

Many of the over 6,000 water systems in Washington are clustered in areas that have experienced or that are experiencing growth-related problems. These systems have been built according to a variety of different standards, making it difficult to join them together in the future as areas incorporate or annex to a city or utility district. Consequently, some of these water systems often must be replaced, which results in an unnecessary duplication of expense to the utility and its customers.

In addition, there are several different planning requirements that directly affect water systems, as well as land use. There has been no established process for assuring that water system plans are compatible with those of neighboring water systems, or that such plans are compatible with, or incorporated into, adopted county plans and policies.

The PWSCA embodies the principle of plaicng responsibility, and therefore accountability, at the level of government closest to the management of the service. Success of this principle depends upon water utilities teaming with local planners, health agencies, water resource managers, and other local governmental decision makers in establishing and administering water system development policies. Several key events were instrumental in developing the principle:

1. The American Water Works Association "Action Now" program was developed to counter attacks by groups claiming the need for substantial improvement in service and reliability of the nation's public water systems. If Washington and other states could pursue an aggressive, utility-based approach to solving water system problems, perhaps there would not be a need for Federal legislation with its typical regulations discouraging innovation and interfering with management prerogatives.

2. The Washington State Board of Health Water System Regulations, adopted in 1971, recognized the need for water system planning by requiring water utilities serving over 1,000 customers, to prepare system plans addressing their future needs, and by developing a program to meet those needs.

3. Referendum 27, a $50,000,000 bond issue, was approved by the state's voters in 1972. It provided financing

> "to assist in the development of water systems which will be able to provide all the water supply needs of a given area in an efficient and reliable manner consistent with community goals."

This was accomplished by maximizing coordination of water system plans and facilities within regional areas. For this purpose, 40% construction grants and 100% planning loans were made available.

4. In 1976, the State Health Agency, in cooperation with the University of Washington and the State Associations of Cities and Counties held a conference entitled "Impacts of Growth on Water Utilities." The consensus of the two-day program was that planning is an important and necessary function of water utilities, and that planning should be a cooperative effort between water utilities, resource agencies, and local governments with land use responsibility.

5. The northwest drought of 1976 vividly accented the competition for water resources as communities realized how dependent they were on a reliable source of water.

The PWSCA was designed to facilitate the coordination necessary to insure efficient water system planning and development. The law is based on the fundamantal premise that water system planning must be coordinated with, even integrated into, land use planning to meet the overall needs of the community.

The PWSCA of 1977 establishes a step-by-step process, with water utilities and local government providing the planning initiative, to accomplish a unified CWSP for given geographical or regional areas. If the steps are rigorously followed, water utility managers will work with land use planners to jointly prescribe how water will be provided for new development and in situations where changes in density lead to higher water demand. This includes answers to questions such as: Is there an adequate source of water? Who will distribute the water? Under what circumstances? Who will pay for the service? When will water be available?

Although the law was primarily aimed at dealing with water utility development in rapidly growing areas surrounding most of the state's larger cities, it applies equally well in smaller, more rural communities. The following is a brief description of the coordinated planning process:

Step 1.—A county or the State Health Agency may initiate preparation of a preliminary assessment. The purpose of a preliminary assessment is to determine the status of water system and land use planning in the area, and to evaluate the amount of coordination which is occurring between water utilities and land use activities. This action may be taken whenever one or both of the governmental agencies are suspicious of problems or upon request from other agencies, water utilities, or pressure from citizens.

Step 2.—The information contained in the preliminary assessment should enable

a county, group of counties, or the State Health Agency to make a decision whether to designate a general area a critical water supply service area (CWSSA). They will use two basic questions as criteria, the answers to which will be documented in the preliminary assessment:

1. Is water system development consistent with, or coordinated with, other water utility plans, and with adopted plans or growth policies, or both, of local governments in the area?
2. Are the water systems able to provide an adequate water supply to meet the needs for the general area? Adequacy is measured by both quality (Federal safe drinking water parameter), and quantity (reliability of service). Water supply needs may be existing or in terms of future demands. The action of declaring a WSSA triggers a series of important steps, because the specified time limits for accomplishing the coordinated planning are based upon the date an area was declared.

Step 3.—A Water Utility Coordinating Committe is appointed by the agency which declared the CWSSA. The committe serves as the basic building block for achieving maximum local coordination by assuming responsibility for the following tasks:

1. Analyze growth potential of the area and water system capabilities in order to recommend specific external boundaries.
2. Assemble water system plans from the individual utilities and direct the development of a coordinated plan for efficient provision of water within the CWSSA.
3. Submit a petition for water reservation for the area if future water source is a concern.
4. After the completion of the major work components, monitor implementation of the plan.

Step 4.—The county legislative authority makes the final determination of the external boundaries of the study area after considering the committee's recommendation and holding at least two public hearings. Adoption of the boundaries is another key step since it signals the beginning of a 2-yr (maximum) planning process.

Step 5.—The next major step is development of a CWSP, directed by the Water Utility Coordinating Committee. Two tiers or levels of planning make up the CWSP:

1. The individual system plan.—This intra-system plan deals with development of water system facilities within each utility's agreed upon future service area. (Many water systems, particularly those with over 1,000 service connections, have already developed this intersystem plan as a result of the Board of Heath's 1971 regulations or requirements relating to Referendum 27 grants.)
2. Regional supplement.—This intersystem, regional, or "umbrella" plan is aimed towards finding solutions to areawide concerns (those water system or planning matters which transcend the boundaries of individual water systems, thereby affecting the area as a whole).

Step 6.—Once the CWSP is completed, it undergoes review by the county government to insure that proposed water system improvements will be consistent with county and local land use plans and growth policies. If the county objects to all or a portion of the plan, at least two months or negotiations with the committee must take place in an attempt to resolve conflicts. Failure to resolve conflicts would result in the State Health Agency determining which portions of the plan to implement on a case-by-case basis—a fate likely to be unfavorable to both water utilities and county government. The plan also undergoes review by the State Health Agency to assure that all the necessary topics have been considered and proposed facilities are adequately designed.

Approval of the CWSP does not indicate an end to the coordination process! The plan is dynamic in several ways. First, an update to both the individual utilities plan and regional supplement must occur every 5 yr or sooner, if growth occurs more rapidly than expected. Secondly, every new water system facility or extension must be approved by the State Health Agency based on the plan. (If not consistent with the plan, the plan must be revised or the proposal must be altered to be consistent with the plan before it will be approved.) Finally, the Water Utility Coordinating Committee, as previously mentioned, is intended to be an ongoing forum to monitor the plan and consider mutual issues as they arise.

To date, six critical water supply service areas have been declared under the PWSCA. Four of these are in metropolitan areas subject to rapid growth, and counties are attempting to organize the utilities for the efficient provision of the water supply. The other two are in areas traditionally rural in character, but experiencing growth-related problems. Both quantity and quality of water supply are serious concerns in the latter areas. Eleven additional counties out of 38 in Washington are considering implementation of the 1977 law.

WRA

The state's WRA of 1971 was an attempt to establish a major policy for the future use of state waters. This policy statement was stimulated through studies conducted by Arizona and California for the purpose of evaluating possible diversion of Columbia River water into those states to augment shortages. It was felt that, in order to utilize Washington's water for the best interests of the people in the state, a solid data base and well-articulated water policy would have to be developed.

Initial research under the state law indicated that, despite its reputation for a wet climate, Washington does not have a surplus of water. Competition among users of the state's water supply loomed as the significant, if not potentially volatile issue. Three of the largest contributors to Washington's economy, i.e., hydroelectric power, agriculture, and fisheries, all depend upon water. The WRA charged the State Department of Ecology with: (1) Identifying existing conflicts among water users; and (2) establishing programs to insure beneficial use in managing the water resource.

The key to developing and understanding water policy is the concept of beneficial use. Indeed, most of the law deals with expansion of that concept in terms such as "enjoyment," "compatibility," "maximum net benefits," "quality of the natural environment," "multipurpose," and "conservation."

But the only policy statement which singles out a specific beneficial use reads, "Adequate and safe supplies of water shall be preserved and protected in potable condition to satify human domestic needs." To accomplish this policy, the State Department of Ecology was given broad new authroity to establish a process for reserving future water source.

What is the significance of this reservation authority? Water utilities which looked ahead to their future demand, and therefore need for an additional source, have been faced with a chaotic system of applying for water rights, and periodically extending the date the water would be put to full use. Washington, like many other western states, has based its water right regulations on the Doctrine of Prior Appropriation, i.e., first in time, first in right. Under this doctrine, a utility which applies for a water right must put the water to use within a scheduled time frame, or that water may be allocated to another user. To assure an adeuqate quantity of water, public water systems have found it necessary to construct source facilities either ahead of the time they will actually be needed, or in lieu of developing more effective methods to augment their source. This situation has high potential for inefficient use of capital, as well as to cause havoc with an established water utility expansion program. Sound water system planning is therefore discouraged. Using water rights in this manner was never intended and has resulted in a haphazard, high-risk approach in attempting to tie up enough water to supply future utility needs.

Through their reservation authority, the State Department of Ecology has established a process enabling domesitc water utilities to set aside enough water to meet long-range future needs. The philosophy may be analogous to banking. Water is set aside to supply future demand for an entire region. As growth occurs and domestic water is needed, the utility responsible for supplying that need draws an increment of water out of the regional pool to develop as an additional source. This is accomplished in accordance with a regional planning document, the CWSP.

The water source is an integral part of good water utility planning. It is important to the utility to be able to count on enough water when the need arises. Knowing how much water is available and where it may be withdrawn makes it that much easier to design the facilities required to add the water to the system. If water cannot be reserved due to lack of quantity, overappropriation, or other reasons, the utility will know well in advance that: (1) It will have to obtain water elsewhere; (2) it will have to enact a strict water rationing program; (3) it will have to evaluate various water uses to determine if water of a lesser quality can be substituted for some uses (industrial, irrigation, etc); or (4) local land use authorities will be forced to curtail growth in the area.

The reservation program is significant in yet another sense. The CWSP is a document prepared in a cooperative atmosphere among the water utilities and other affected parties in the region.

It is primarily intended to: (1) Justify future water needs within the region; and (2) identify an efficient, cooperative program for utilization of water set aside for regional domestic use.

The planning requirement establishes a framework or mechanism for making it easier to deal with regional water source issues. It also sets the stage for consideration of such benefits to individual utilities as consolidation for more efficient operation, interties for increased emergency response or better use

of sources, and services areas for more organized planning and system management.

Two regions in the state have secured a future source since the reservation process was established in 1976. Numerous other areas are currently preparing their own CWSP in anticipation of reservation requests, including Seattle and its metropolitan area.

Now public water utilities in Washington have a clear process designed to allow them to plan ahead for supplying their future needs without constant fear that the water they are counting on will be lost to a competing use. Financing of capital improvements should also be considerably easier than the present hodgepodge water rights system. Through implementation of the WRA, beneficial use has been defined in part as a more organized, efficient means to provide ample drinking water for future generations.

Common Bond—Coordinated Plan

The most important element of each of these state laws is the CWSP. The plan, a comprehensive strategy for the management of water resources, land use development, and provision of domestic water, is likely to become the most usable and important document for the territory it covers. By identifying who is responsible for providing water in a given area, how and when that water will be provided, and how much, others involved in land use management will have an easier job predicting consequences of their actions.

The two parts of a CWSP, i.e., the individual utility plan and the regional supplement, have been defined more completely in a publication entitled "Plan Contents Guidelines." It serves as a guide of topics expected to be covered, as well as criteria for plan review.

Individual Utility Plans.—The individual plan that each utility must prepare will vary in detial according to the size of the system and its intentions for future expansion. The most comprehensive and detailed plan is required for public water systems with more than 1,000 services. As a minimum, it should address five major topics.

1. Basic planning data should include a general description of the water system's existing and future service area including history of the water system, present water consumption and demand records, and an inventory of related plans affecting the utility. Present land use plans and population distribution patterns should be reviewed, as well as projected changes, in order to ascertain water requirements in areas anticipating service from the water system.
2. The inventory of existing water system facilities should describe, and critically review, the present condition of every element of the existing system such as source, treatment, storage, transmission, and distribution facilities. A hydraulic analysis should be performed and all background information should be thoroughly reviewed. The status of existing water rights must be reviewed, and so must conformance with the State Board of Health's (and Safe Drinking Water Act's) minimum water quality standards. Consideration of applicable fire-flow performance standards and the ability of the utility to meet those standards should complete the inventory and analysis of the existing system.
3. Adequate mapping must be included in the plan so that at least the following

factors affecting the water system are identified: (1) Existing and future service areas; (2) existing and projected land use patterns, including zoning; (3) present and future population distribution; (4) fire-flow classification; (5) existing and future high water use areas; (6) critical elevation and pressure zones; and (7) existing and future water system facilities including sources, treatment, storage transmission lines, major distribution lines, booster pumping stations, and interties with other systems.

4. Miscellaneous items of consideration should include an operation report which outlines routine maintenance and operation, water quality monitoring, cross-connection control, emergency plan, and identification of responsible personnel. Agreements for future service areas, interties, or shared facilities, or both, or documentation of any attempts to reach such agreements, must also be provided. If water availability is a problem for the utility, a more complete consideration of the resource alternatives should be provided, which may include a ground-water study, water shed control programs, analysis of interbasin transfer, etc.

5. Finally, formulation of needed water system improvements results from the data presented in each of the preceeding sections. Optional methods of meeting those needs and associated costs should be described and assessed. Recommended improvements should be selected and justified along with a suggested time schedule (based on either fixed dates or growth factors) and proposed financing program.

Regional Supplement.—The regional supplement was designed to be flexible based upon the particular situation in each area. In some cases, it could include a summary of items pertaining to the entire region which have already been addressed in each individual water plan. In other instances, this regional document may serve as a guide for preparation of the individual plans by identifying major areawide policy such as conditions for water system expansion, desired levels of service, and scheduling of new source development. The regional supplement should contain at least the following information:

1. The relationship between water system development in the region and other adopted plans which affect land use and growth.

2. Documentation of agreement on future service areas into which each utility will expand to provide water service. This is intended to avoid conflicts over who will serve specific areas, overlapping planning, and costly duplication of facilities, while giving each system the assurance that it will be able to implement its plan without interference from another water utility.

3. Minimum design standards which apply to new system facilities within the area. With these standards, new systems will be constructed to the local area's design criteria so that they could be readily absorbed into larger systems (no matter what the reason) while assuring the citizens of the area a minimum level of water service. Fire-flow protection must also be incorporated into these standards.

4. An identification of procedures and conditions for authorizing new water systems to locate within the critical water supply service area. This would guarantee an orderly process of assessing whether new systems are needed

on either a temporary or permanent basis and serve as a mechanism for applying the minimum design standards.

5. An assessment of joint-use or shared water system facilities which would be beneficial to the area as a whole, such as emergency interties between systems and regional source or storage projects.

6. a program for developing and managing additional sources within the region consistent with requirements for reservation of future water supply.

The CWSP then becomes the two-part product of a cooperative planning process. Because all water facility projects and land use decisions are based upon this document, it becomes the common bond which unites development of the water resource with land use management. And because water utility development and water resource management depend upon this document, it becomes the common bond linking the supply of water with its use.

Conclusion

As a common bond linking water resources, land use, and provison of drinking water, the CWSP will enable decisions to be made in the best interest of all three elements. It will also enable decision makers at both the county and water utility levels to better assess the potential effects of their decisions.

When the CWSP is completed, each water system, as a user of the resource, will have determined its future needs, and can begin to fulfill those needs with the assurance that: (1) Water use will be consistent with land use plans and policies for the area; (2) neighboring water systems will not be competing with or infringing upon their service areas; and (3) their future source will not be allocated to another type of water use.

CWSP, developed in a cooperative manner at the local level and enforced by state agencies are gaining wide acceptance in Washington. Therefore, a high probability of success is predicted for the new approaches devised to bring together the inseparable elements of water resources, land use, and provision of drinking water for the first time in the state's history.

JOURNAL OF THE WATER RESOURCES PLANNING AND MANAGEMENT DIVISION

URBAN STORMWATER MANAGEMENT IN SOUTHEAST

By David H. Howells,[1] F. ASCE and Neil S. Grigg,[2] M. ASCE

INTRODUCTION

This paper summarizes the findings of the Southeast Conference on Urban Stormwater Management, held at North Carolina State University April 10–11, 1979. Invited participants included key Federal, state, and local officials, water-resources research institute directors, and other representatives of the university community. The conference was the third of a series directed toward major water-resource problems of Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia.

ROLE OF STATE GOVERNMENT

The role of state government in urban stormwater management in the Southeast is highly variable. Drainage and detention has traditionally been a function of local government. Flood plain management, with its ties to land-use zoning and regulation, has a similar history except for the Federal flood-control and insurance programs, where state government has often served as a facilitator and intermediary. The states have taken their strongest leadership in the areas of stormwater pollution control and, to a lesser degree, erosion and sedimentation control. The following discussion summarizes state programs in the Southeast with respect to these four elements of urban stormwater management.

Drainage and Detention.—With the exception of transportation departments, state agencies have had little impact on local drainage policies. The single exception is the Florida Department of Environmental Regulation which has overview and coordination authority with respect to Florida's water-management districts.

[1]Prof. Emeritus, North Carolina State Univ., and Univ. of North Carolina at Chapel Hill, 124 Riddick Building, North Carolina State Univ., Raleigh, N.C. 27650.

[2]Asst. Secretary and Dir., Div. of Environmental Management, North Carolina Dept. of Natural Resources and Community Development.

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Some of these districts have very extensive planning and management responsibilities for drainage and detention in their areas of jurisdiction.

State enabling legislation in support of local initiatives is generally considered to be adequate, and there appears to be no perceived need to expand state programs in this area.

Flood Plain Management.—The principal activities of state government in flood plain management have been the enactment of enabling legislation and facilitation of local government participation in the National Flood Insurance Program administered by the Office of Federal Insurance and Hazard Mitigation (FIHM) of the Federal Emergency Management Agency. The state function is largely limited to coordination, processing of community applications to FIHM, assuring consistency and public awareness, and developing flood-warning and emergency services.

The most significant problem associated with administration of the Flood Insurance Program has been lack of monitoring to determine local compliance with program requirements, particularly with respect to the adoption and enforcement of land-use controls in flood-hazard areas. Many local governments do not have the planning and management capability to carry out their obligations under the program, and most states have not moved to provide the needed technical assistance and institutional support. Georgia attempts to evaluate compliance with program requirements, but its efforts have been severely constrained by lack of resources. Virginia appears to have done more than most to cope with these problems. Staff of the State Water Control Board assist communities in the development of needed ordinances. The Virginia Flood Damage Reduction Act calls for a joint inspection program between the board and communities to determine the effectiveness of local flood plain management, including efforts to preserve the capacity of the flood plain to carry and discharge a 100-yr flood. The degree to which this program has been implemented, however, is unclear. Virginia's Uniform Statewide Building Code now has a section on floodproofing. This requires new or substantial structural improvements to be built at or above the 100-yr flood elevation. Enforcement is the responsibility of local building inspectors.

North Carolina enacted a Floodway Regulation Act in 1971 to specify means for the regulation of artificial obstructions in floodways. the act authorizes local governments to delineate floodways and adopt regulatory programs. The State Environmental Management Commission is authorized to delineate floodways and adopt regulatory programs where the reach of a stream exceeds the jurisdiction of a single local government or local initiative is not taken; however, these state powers have never been exercised. The potential of the Floodway Act for mounting a statewide program has not been realized due to lack of a sense of urgency. The North Carolina department of Natural Resources and Community Development recently concluded that a more effective flood-damage reduction effort is needed. It proposes to coordinate and deliver state and Federal resources to communities with flood problems and assist in the development of a flood-damage reduction strategy appropriate to individual community needs. As a first step, the department is forming a State Flood Damage Reduction Task Force to bring together state and Federal agencies with responsibilities in this area. The task force will be asked to assess state and Federal resources available for flood-damage reduction efforts, establish priorities among flood-

damage areas, and coordinate the delivery of state and Federal assistance to communities with flood problems. A professional staff member has recently been retained to provide leadership to this effort.

Florida is attempting to discourage undesirable growth in flood-hazard areas through the following techniques: (1) Department of Environmental Regulation control of 201 facilities planning for sewage treatment facilities pursuant to the President's Executive Order on Flood Plains; (2) interagency agreement between the Department of Environmental Regulation and the Department of Transprotation regarding design and location of roads in flood-hazard areas; and (3) a gubernatorial executive order which addresses public investments in flood hazard areas.

Erosion and Sedimentation Control.—Half of the Southeastern states have enacted erosion- and sedimentation-control legislation applicable to urban areas. South Carolina was the first to act when it adopted a sediment-control act in 1971. North Carolina and Virginia followed in 1973 and Georgia in 1975. There are some significant differences.

The basis for the South Carolina program is enabling legislation which authorizes the establishment of local sediment-control programs by county ordinance. It restricts grading or other land disturbance without a prescribed county permit and in accordance with an approved grading, erosion, and siltation plan. Approved plans must be certified by a professional engineer or soil conservationist and approved by the local soil- and water-conservation district. Only three counties have adopted erosion-control ordinances to date. Several others are in various stages of development. Two of the three counties with ordinances have relatively inactive programs. One county program has shown exceptional results. Lexington County has an effective sediment-control program for unincorporated areas and has entered into agreements with most of its municipalities to enforce the ordinance within their boundaries as well. The ordinance is administered by a county sediment-control officer with assistance from public works, engineering, and conservation district staffs. Enforcement is coordinated with subdivision approvals and issuance of building permits.

In contrast to South Carolina, the North Carolina legislation places responsibility in a State Sedimentation Control Commission with authority for delegation to other state agencies and local government. If local government fails to adopt or enforce a program, the commission is empowered to assume responsibility at the state level. The commission has exclusive jurisdiction for establishing sedimentation control regulations for local, state and Federal agencies, nongovernmental entities having right of eminent domain, and projects funded with any state or Federal funds.

The North Carolina Sedimentation Control Act established regulatory standards with respect to buffer zones, angle of slopes, and ground cover. Control facilities must be able to withstand a 10-yr rainfall. Release velocities must be controlled so as to prevent channel erosion at point of discharge. There is no provision for the control of downstream erosion. If the velocity can be controlled at the point of discharge, detention is not required. There are suitable provisions for enforcement and penalties.

Seventeen of North Carolina's 100 counties and 21 municipalities have enacted sedimentation control programs. Some local programs encompass more than one unit of government. Failure of public agencies to forcefully administer

sediment-control programs, the unwillingness of some local governments to assume this responsibility, and limited staffs have been the principal problems.

A somewhat different approach was taken in Virginia. Here, the legislation requires every local government to adopt an ordinance which meets standards set by the state Soil and Water Conservation Commission. Minimum standards for construction sites are contained in an Erosion and Sediment Control Handbook developed by the Commission. There are no requirements for on-site detention or control of the peak rate and volume of stormwater runoff leaving the site. The Commission has proposed revision of the handbook to include stormwater management criteria for the control of erosion. While the Commission recognizes the need for stormwater management controls in urban areas, it has avoided statewide controls in the belief that they would not be applicable to many areas. As an alternative, it will soon undertake the development of a guidelines manual for stormwater management in localities which need them. The manual will address both the quantity and quality aspects of stormwater runoff, including design criteria.

All of the counties and cities and nearly half of the towns in Virginia are now operating under an approved local erosion- and sediment-control plan. Citizen support is lacking in some communities because of the mandated nature of the program. Requiring the local adoption of an ordinance is one thing—implementation is another. The provision for funding calls for $150/site charge regardless of size. This is insufficient for the larger developments.

In contrast to the enabling legislation of South Carolina and mandated local programs in Virginia, the Georgia program approximates the local-state alternative of North Carolina. The Georgia Erosion and Sedimentation Control Act provides for local adoption of control ordinances or state enforcement where local jurisdictions fail to act. There are important exemptions that are of significance to urban areas. These include projects on Federal lands, construction and maintenance by local governments, and construction by such important agencies as the state Department of Transportation.

As elsewhere, erosion- and sedimentation-control plans in Georgia must be prepared and a permit obtained before specified land-distrubing activities may be undertaken. Plans must be reviewed by local soil and water conservation districts before permits can be issued by local governments. Local governments have the option of adopting an ordinance which meets or exceeds minimum requirements of the act or accepting the authority of the Georgia Environmental Protection Division to issue necessary permits, conduct inspections, and enforce rules until such time as an acceptable ordinance is adopted locally.

By March 1979, 90 of Georgia's 159 counties and 147 of 531 incorporated municipalities had adopted local ordinances. The intent of the act was to encourage local adoption of ordinances rather than statewide regulation; however, nearly half of the counties and about 70% of the incorporated municipalities have not adopted local programs yet.

While the exempted activities leave many important types of land-disturbing activities uncovered, the Georgia Division of Environmental Protection believes there may be alternative means for dealing with these. Federal projects are subject to internal agency guidelines and project specifications. The Georgia Department of Transportation has its own design criteria and specifications for erosion and sedimentation problems.

In contrast to North Carolina act, the Georgia act does not provide penalties for violations or for failure of local governments to enforce their ordinances. The George Water Quality Act may also be of some help in this regard. Rules under that act provide for enforcement action in cases involving land-disturbing activity. A unique provision empowers the state Environmental Protection Division to issue permits for nonpoint sources of pollution. This has potential for application to erosion and sedimentation problems.

Stormwater Quality Management.—There has been a growing awareness of the pollutional effects of stormwater runoff on the quality of water in receiving watercourses since this phenomenon was first investigated by the U.S. Public Health Service more than 20 yr ago. The present concern has its roots in Section 208 of the Federal Water Pollution Control Act which calls for the development and implementation of areawide waste treatment management plans. Emphasis of the planning process has been on nonpoint sources of pollution from stormwater runoff. Urban areas are viewed as an important source of nonpoint pollution. The act and subsequent regulations called for the governors of the various states to designate areawide planning agencies capable of carrying out the 208 planning process in highly urbanized and industrialized areas and to assume this responsiblity for all undesignated areas. The national program is administered by the United States Environmental Protection Agency (EPA) which operates through state counterpart agencies. Thus, the state agencies are responsible for the planning process subject to EPA regulations, guidelines, review, and approval.

Planning under Section 208 has been the primary mechanism for developing a statewide approach to the management of urban stormwater runoff. Federal planning guidelines require that 208 plans include an element which identifies existing and future stormwater system improvement necessary to meet applicable water quality standards and estimates the costs of such improvements. Since designating concentrated storm-sewer discharges as point sources in 1976, EPA has been attempting to develop an appropriate approach to the permitting of such discharges. Proposed regulations are expected to clarify the Federal permitting strategy and provide direction for state stormwater permitting activities. Final regulations on storm sewer permits and best management practices have not been issued yet.

In contrast to the control of pollution from municipal, industrial, and other point source discharges, through waste reduction and treatment, emphasis on correction of pollution from nonpoint stormwater runoff has been on studies and investigations to establish the cause-and-effect relationships and the development and adoption of best management practices to reduce pollution at the source. While there is general agreement that certain practices will enhance water quality, there is little quantifiable information available as to the effectiveness of the practices in reducing pollution loads, effects on receiving water courses, and the benefits to be gained through pollution abatement. By and large, the first generation of 208 reports have not met this need, and further investigation is required before an array of best management practices can be developed with any certainty of the relative benefits to costs involved. In the meantime, improvements have been realized through the adoption of erosion and sedimentation programs, short-term storage in detention basins, improved-street cleaning procedures, and other measures.

There is reason to believe that the ultimate practical solution to the control of pollution from stormwater runoff may lie in the full integration of water quality management with other aspects of urban stormwater management. The 208 program provides at least a partial vehicle for this objective. The effectiveness of street sweeping can be assessed in terms of the removal of polluting residues rather than just the visual appearance of the street. Drainage and detention systems can be designed for residue collection and removal as well as for the control of flooding. Buffer strips along urban streams can serve as filtering devices for overland runoff in addition to more limited landscaping objectives. There are many opportunities for implementing control measures short of the mandatory imposition of best management practices. Again, the key is to consider drainage and detention, erosion- and sedimentation-control, flood plain management, and the control of pollution from stormwater runoff as interrelated—not isolated—elements of urban stormwater management.

State designation of areawide agencies for 208 planning has varied from a high of 12 in Florida to 2 in North Carolina. Objectives and procedures used by the designated agencies have been highly variable, and the final products reflect this. Some agencies have undertaken detailed monitoring strategies in an effort to develop reliable data on the effects of various land-use practices on associated stormwater runoff quality. Others have relied on model studies and other forms of estimation utilizing published data from investigations elsewhere.

The Alabama Water Improvement Commission has expressed general satisfaction with causal data and other findings from two of its three areawide agency studies. One, a study of the Mobile region, is reported to have identified the source of pollution responsible for the deterioration of bacteriological quality in Mobile Bay and closure of oyster-growing areas. The response from other state agencies is more cautious and less hopeful that the first-generation reports have met their objectives of providing a basis for the management of nonpoint source pollution from urban stormwater runoff.

Florida appears to have moved furthest toward a management program while sharing the views of sister states that reliable data on pollution from stormwater runoff is not yet sufficient to firmly establish cause-and-effect relationships and the relative effectiveness of best management practices. Florida anticipates that such information will eventually flow from the 208 program. The state Department of Environmental Regulation has taken steps toward management of stormwater discharges by initiating a regulatory process. This will be refined and extended as better information develops. Rules have been adopted requiring the reporting of all new stormwater discharges. If the department determines that such discharges will have significant impact on water quality, permits will be required. Existing discharges are also subject to permitting authority if determined to have significant impact. There is provision for delegation of this authority to local or regional governments where they demonstrate the capability to administer the program.

The relationship of water quality to other aspects of stormwater management is reported to be tangibly recognized in Florida. Rulemaking has been initiated to establish a state-level process for the selection of Federal water resource projects through which the projects will be encouraged to include water-quality management practices. Flood control and drainage projects, for example, will

be expected to utilize detention to reduce pollution as well as to meet other objectives. Florida has embarked upon a statewide regulatory and management strategy to substantially reduce water-quality degradation from stormwater runoff with emphasis on local implementation. The biggest problems are viewed as lack of sound data, inadequate knowledge of the efficacy of management practices, and insufficient resources and personnel to do the job.

Georgia is the only southeastern state other than Florida to have specific legislative authorization for the management and permitting of both point and nonpoint sources of pollution. Past efforts have been focused on domestic and industrial point sources. As elsewhere in the region, efforts are now being made to evaluate the significance of nonpoint stormwater runoff sources through the 208 planning process. Permits are not presently required for storm- or combined-sewer outfalls, since no significant efforts have yet been made by the State Environmental Protection Division to evaluate the magnitude and impact of associated pollution loads or to demonstrate impairment of beneficial uses of water. The 201 Facilities Planning Program is being used to evaluate the impact of combined sewer overflows and costs of remedial works for the state's five largest urban regions.

The preparation of the urban stormwater element of the statewide 208 plan for Georgia proved untenable because of lack of sufficient information to identify areas throughout nondesignated portions of the state where urban stormwater was causing water-quality problems. Instead, emphasis was placed on development of an overall nonpoint source modeling strategy to generate the information necessary to evaluate urban stormwater quality problems. The specific objective of the strategy has been to provide guidance for the incorporation of nonpoint source wasteload allocation methods into the state's strategy for water-quality management. The strategy report (1978) concluded that sufficient data do not now exist to quantify the magnitude of nonpoint source pollution in Georgia or the effectiveness of nonpoint source control measures. The development of an overall state strategy for management of urban stormwater is the objective of an on-going study funded by a supplemental 208 grant. Its goals are to:

1. Compile and evaluate existing stormwater data.
2. Conduct a statistical analysis of available water quality data to determine whether the impact of stormwater runoff on water quality can be evaluated through existing monitoring data.
3. Evaluate biological and physical characteristics of streams and drainage systems in selected areas.
4. Review urban stormwater runoff assessment and monitoring techniques and impact studies.
5. Describe current stormwater management techniques in selected urban areas.
6. Review potential management problems.
7. Recommend activities necessary to support the development of a prudent statewide approach to the management of urban stormwater runoff.

Inadequate information remains the most significant impediment to the management of stormwater quality in Georgia. Other related problems are the massive costs of urban stormwater treatment and institutional problems associated with implementation of needed programs.

The situation in the remaining southeastern states is similar to Florida and Georgia with the exception of legislative authorization for regulatory programs. Nearly all states have produced manuals suggesting best management practices for urban stormwater management. These generally represent a compilation of the present state-of-the-art and reflect present limitations in this area. They are not action documents and must be viewed as only first steps in the development of comprehensive statewide plans. Lack of reliable data on cause-and-effect relationships between stormwater runoff and impact on receiving water courses and costs of remedial practices is the principal limitation to greater progress in this field. Virginia reports that it is currently developing a nonregulatory management program to implement best management practices in watersheds with identified urban runoff problems. Implementation will rely on the availability of technical and financial assistance to the top-priority watersheds.

Investigations by some areawide 208 agencies, state agencies, and the Tennessee Valley Authority have concluded that urban streams in general suffer from severe biological degradation. This is attributed to surface runoff, leaking sewers, unpermitted point discharges, solid waste, and erosion. Some of these sources, at least, are subject to control under existing state and Federal programs and need not be viewed as a part of the urban stormwater runoff phenomenon. But the surface runoff component remains elusive. The Environmental Protection Agency, in cooperation with state agencies, has scheduled four detailed field studies in the region to help meet this need. The locations are the Tampa-St. Petersburg area in Florida; Winston-Salem, North Carolina; Waccamaw, South Carolina; and Washington, D.C. Each will investigate a different hydrological pattern of interest to the region.

Local Government Programs

The implementation of urban stormwater management programs is the function of local governments. Insights into local programs were provided by reports (1) on slected municipal and regional programs and analyses (1) of local stormwater management ordinances. The former were provided by spokesmen for Mobile, Alabama; Tampa, Florida; the South Florida Water Management District; the Atlanta Regional Commission; Charlotte, North Carolina; Knoxville-Knox County, Tennessee; Nashville, Tennessee; and Fairfax County, Virginia. Critiques on urban stormwater management ordinances were presented by analysts from the Georgia Institute of Technology and the University of North Carolina at Chapel Hill.

Drainage and Detention.—Growing recognition of the need for improved drainage and detention systems in metropolitan areas has been a rather recent phenomenon. Tampa first established a drainage section within its Department of Public Works in 1940. Mobile evidenced little interest in improving urban drainage until 1972 when action by the legislature to remove municipal immunity from lawsuits involving damage from improper drainage, coupled with severe rainfall and flooding, sharpened awareness of the problem. Accelerated urban development following World War II, with its wholesale transformation of land-use and related hydrology, was undoubtedly the controlling factor.

The types of problems encountered and response at the local level are heavily influenced by the topography and hydrology of each metropolitan area. The

Florida experience encompasses low flatlands and high water tables where wetland reclamation, drainage, and flood control have been matters of long-term concern. Cities like Mobile first occupied the flood plain and then expanded into the adjacent hills. Drainage problems there tend to focus at the juncture of fast-moving highland drainage with tidewater. Knoxville is underlain by extensive limestone formations. Underground solution channels provide the principal drainage outlets at many locations. Sinkhole, rather than surface drainage, is found throughout the area. The Atlanta Metropolitan Region straddles a subcontinental ridgeline with half the drainage flowing to the Atlantic Ocean and half to the Gulf of Mexico. Many streams originate within the region, are small, and particularly vulnerable to pollution. Urbanization of headwater basins is also characteristic of Charlotte and many other metropolitan areas of the region.

The need for detention in urban stormwater management is also closely associated with local topography and hydrology. In Florida, this can be attributed to the difficulties of draining flat topography, need for large conduits at very flat slopes, the distance from drainage areas to receiving waters, and the relatively high cost of such projects. The Tampa system includes 50 detention basins, and the city is considering more through the purchase of properties in flood-hazard areas for this purpose. Detention basins are viewed as more cost effective than reconstruction or improvement of the existing overloaded drainage system. Mobile must provide detention wherever possible to dampen the impact of high-velocity upland waters on tidewater areas. These range from siting in flood-hazard areas where structures can be relocated to increased use of park reservoirs and new upstream detention facilities. Knoxville is now requiring developers to incorporate detention facilities when in the public interest. Detention structures are included in virtually all new developments in DeKalb County (Atlanta Metropolitan Region).

Development in Fairfax County, Virginia, adjacent to Washington, D.C., has been accompanied by the construction of P.L. 566 small watershed flood-retarding impoundments.

Operational problems have both common and site-specific characteristics. The most severe of these has been the question of maintenance. DeKalb County has begun to assume responsibility for the maintenance of new facilities, though owners retain responsibility for older ones. Tampa has found that maintenance requires continuous attention. It has experienced poor water quality and mosquito breeding. Fairfax County maintains all P.L. 566 reservoirs and other detention basins serving individual homes and condominiums. All other facilities are maintained by the owners. Maintenance agreements are executed before approval of development plans and are recorded as a covenant to the property. A silt-removal program involving annual dredging of the P.l. 566 impoundments has been established.

The use of detention basins has been accompanied by other supportive measures at some locations with mixed results. Tampa reports that infiltration facilities can be useful, but that poor maintenance by owners has made the city reluctant to use them. Porous asphalt is used for parking areas, though there is concern over sealing and reduced permeability through deposition of sediments in aggregate voids. It is accepted only when runoff can be otherwise retained in event of failure. Underground retention through large perforated pipes surrounded with open graded aggregate in trenches is viewed as an alternative to detention basins.

Fairfax County permits infiltration pits, rooftop storage, parking-lot detention, and underground detention as well as detention ponds.

Design criteria for drainage and detention range from no increase in postdevelopment discharges over those experienced under predevelopment conditions to the retantion of a 10-yr frequency storm. DeKalb County, in the Atlanta Metropolitan Region, now specifies that the stormwater runoff rate cannot be increased by more than 1 cfs (0.028 m^3/s) for the 100-yr frequency storm. This requires the inclusion of detention structures in virtually all new development. Developers are required to prepare hydrologic/hydraulic studies for each project.

In spite of widespread interest in the use of detention, several questions remain unresolved. These include: the question of cumulative effects of many small detention facilities on downstream hydrology; safety considerations and related liability; and maintenance responsibilities. There is a high level of interest among local governments and in the development community in resolving these questions.

Several local government initiatives are of particular interest.

Charlotte.—Charlotte has adopted a Storm Drainage Policy to assist citizens with localized drainage problems. Projects must involve drainage from publicly maintained streets, associated property damage, and areas of less than 1 sq mile. Cost sharing is two-thirds city and one-third area property owners. Drainage petitions must be signed by 51% of landowners in the drainage basin. The public response has been overwhelming, though there are some problems. Property owners whose runoff contributes to flooding, but who are not affected, are reluctant to pay their share of the assessment. The 51% provision also presents some difficulty in that this proportion of a drainage-basin population is rarely interested in a single project. When flooding is severe, the city can order correction and assess the costs without petition.

Atlanta Regional Commission.—The Atlanta Regional Commission adopted the Chattahoochee Corridor Plan as a basis for the management of development in a 48-mile long, 4000-ft wide corridor centered on the Chattahoochee River. The underlying philosophy is that land development should be tailored to the natural features of the land. The corridor is divided into six land-vulnerability categories defined by the composite weighting of vegetation, soils, hydrology, slope, and geology. The Plan specifies maximum land clearance and percent impervious surface for developments in each category. Construction within 150 ft and land clearance within 50 ft of the river is prohibited. Developments can be governed by standards of the next least vulnerability category if detention is provided. The basis for the plan is to protect water quality. The downstream end of the corridor coincides with the city's water-supply intake. There are also important aesthetic and recreational benefits.

Fairfax County.—Fairfax County initiated the development of Master Drainage Plans for major streams and tributaries in 1971. The objectives are to prevent flooding; prevent severe channel erosion and interruption of traffic by flooding; and to protect aquatic ecosystems, wildlife habitat, parks, and recreation areas. An immediate-action plan identifes and describes improvements to make existing drainage systems capable of handling current stormwater runoff. A future basin plan serves as the basis for projected development patterns and land-use plans. Costs of drainage facilities are prorated back up into watershed segments and translated into cost/cfs increase in flow. If the peak runoff rate is estimated

to exceed the rate in undeveloped condition for a 2-hr, 10-yr frequency storm, developers are required to fund their proportion of all required downstream facilities. Assessments can be offset to the extent that on-site detention reduces the projected increased runoff.

Flood Plain Management.—Local flood plain management programs have been heavily influenced by historic siting decisions, topographic and hydrologic conditions, and participation in the Federal Flood Insurance Program. Old Mobile, for example, was built on the flood plain, and much prime industrial and residential property is located there. Because of this and emphasis on industrial development, the city has moved slowly in this area. There was strong opposition by real-estate and development interests to the adoption of a flood plain ordinance until they found that they could not secure flood insurance without it. Minimum elevations for industry floor levels are waived if the city is held blameless in event of flood damage. Leniency is also shown for residential construction where 5-ft elevation above sea level is sometimes permitted if structures are safe from a 10-yr storm.

The Corps of Engineers has made substantial contributions to local flood plain management—particularly in Charlotte and Nashville. Their study of the main urban watershed in Charlotte encompassed flood-damage potential, recreation, water quality, and other aspects of watershed management. Field surveys included measurement of first-floor or living-space elevations of structures and cross sections of stream channels. The data are being used to develop relationships between floor elevations and flood elevations up to a 500-yr frequency. Potential damages will be computed in 1-ft increments for a range of flood-frequency periods. Nonstructural alternatives will be considered. These can now include land acquisition on an 80/20 Federal-state cost-sharing basis. The Charlotte program restricts flood plain development in all water-sheds in excess of 1-sq mile (2.59-km^2) area. Signs identifying flood districts are erected as a public information and enforcement aid. Development of land bordering streams cannot include structures subject to flooding or damage by a 100-yr flood. Final flood elevations, maps, and flood insurance rates have been established, and some 780 policies have been purchased.

The Cumberland River at Nashville crested above the 100-yr level in 1975, and this heightened local interest in flood plain management and other flood-damage reduction alternatives. Corps of Engineer studies have produced flood frequency-damage relationships similar to Charlotte. Reconnaissance studies have been undertaken to determine if structural, nonstructural, or a combination of flood-damage reduction measures are economically feasible and desired by local interests. These will include a preliminary assessment of the effects of future development in the watershed on flood levels. Comprehensive plans may contain small headwater detention reservoirs, a system of levees and one-sided channel improvement in urban areas, relocation, floodproofing, combined recreation and river overflow areas, and early-warning systems. Public participation is a vital part of the planning process. Many people question the use of tax dollars for flood-damage reduction and hold the view that persons subject to flooding have only themselves to blame and the government should not bail them out. Lack of continuity among elected officials and technical staffs, low priority for flood-damage reduction at state and local level, opposition to building restrictions and zoning by real-estate interests, and lack of early involvement of local interests

in the planning process have been problems.

The Fairfax County program started in advance of the Federal Flood Insurance Program through a cooperative effort with the U.S. Geological Survey (USGS) to delineate flood plains. It was also shaped to some extent by the county's participation in the P.L. 566 Small Watershed Program. There is a strong encouragement to leave flood plains in their natural state and the land-use plan contains greenbelt areas traversing some of the major streams. Land uses in 100-yr flood plains are restricted to those with a low damage potential. Any use that has the potential for changing hydrologic or hydraulic characteristics of flood plains require special engineering study before approval. Such changes are monitored, and the flood plain boundaries are revised to take them into account. The county holds the view that successful flood plain management reqiures keeping delineations up to date and maintaining compliance with restrictive ordinances.

Experience in the Atlanta Metropolitan Region demonstrates again that cost effectiveness is not always the deciding factor in considering flood plain management alternatives. The most cost-effective solution to the reduction of flood damage in two highly urbanized watersheds was found to be evacuation and flooding. Despite the availability of Federal funds, there was little local support because of perceived community disruption and effects of floodproofing.

Erosion and Sedimentation

Local erosion and sedimentation programs follow the pattern laid down by state legislation. Where there is no legislation, there are no local programs. It was to be expected, therefore, that only Charlotte-Mecklenburg County, Fairfax County, and Atlanta would have meaningful programs in place. The Charlotte-Mecklenburg County has adopted an ordinance and program that complies with the North Carolina Sedimentation Control Act. Current problems include lack of understanding of the intent of state and local regulations. An additional education effort is needed. Difficulty has been experienced with court enforcement. This has been particularly true where landowners have been in a state of bankruptcy.

Fairfax County initiated an erosion and sedimentation control program under P.L. 566 prior to passage of the Virginia legislation. It has since been revised and updated. Erosion and Sedimentation Control and Public Facilities Manuals provide guidelines and details of compliance for the various county agencies involved and specify engineering criteria for control plans. Annual training courses are provided to update inspectors' skills.

All counties and larger municipalities in the Atlanta Metropolitan Region have local ordinances, but less than one-half of the jurisdictions have ordinances approved by the state. The major reason for this has been the absence of a provision for concurrent review of control plans by the local soil and water-conservation districts, as required by state law. Larger jurisdictions feel competent to conduct review, while the smaller ones are content to rely on the districts. Because Georgia law provides only general standards, much discretion is left to the developer and reviewing official. Implementation is the exclusive responsibility of the developer. In larger jurisdictions where most development occurs, compliance inspection is insufficient and plan implementation lax. The exclusion of all construction projects by public agencies and

development of less than 5 acre leaves 2 significant categories of sediment sources unaccounted for.

Stormwater Quality

Local as well as state concern for the effects of stormwater discharges on the quality of receiving waters has largely mirrored Federal interest expressed in Section 208 of the 1972 amendments to the Federal Water Pollution Control Act. While urban drainage systems were constructed with only stormwater quantity in mind, some contained features that have a significant effect on quality. In Tampa where extensive use has been made of detention basins, for example, there is the opportunity to capture at least part of the first flush effects of runoff. Criteria of the South Florida Water Management District now require retention of the first inch of runoff, or the runoff from a 3-yr storm, whichever is greater. This is normally accomplished through a system of freeboard. About one-fourth to one-half of the first flush can be retained in this way.

The situation in Mobile may be more typical. Here, the 208 plan has identified four management options—all related to street residue. They include trash removal, sewer flushing, catch-basin cleaning, and street sweeping. The latter is believed to be the most promising.

Lack of reliable data to relate land use and stormwater quality to effects on receiving streams and effectiveness of best management practices are major limiting factors, and no breakthroughs are expected until this need is met. The single exception may be the area represented by the Metropolitan Washington Area Council of Government of which Fairfax County is a part. The stormwater-quality problems here are the continuing sedimentation and deteriorating quality of water in the Occoquan Reservoir, Potomac River estuary, and urban streams. The 208 areawide study in this region has included extensive sampling and analysis of the relationship between land-use types and pollution loadings. Basin water quality models have been prepared and calibrated. Correlations have been developed to estimate the effects of best management practices on receiving-water quality. Models are now being evaluated. Local officials believe that existing erosion and sedimentation policies and controls will accomplish major water-quality objectives.

Most older and larger cities in the Southeast have combined sewer systems, and stormwater bypass with accumulated system residues is an important problem. The Atlanta system has 10 major combined sewer overflows. Present plans call for a small amount of sewer separation, capture, storage, and secondary treatment of first flush of overflows for four of these. Plans for the remaining six are not yet complete.

Protection of relatively undeveloped urban watersheds for public water supply can also be a concern. Atlanta has adopted a stormwater runoff control program and zoning to protect such watersheds. Development pressures are likely to encourage zoning variances and rezoning problems. Neither the state nor the Atlanta Regional Commission has authority to insist on strict adherence to the program. There is also a question as to the adequacy even if enforced.

Local Stormwater Ordinances.—Analyses of local drainage ordinances and programs led to a number of significant conclusions and recommendations.

Many urban drainage and erosion control ordinances are being adopted as a result of Federal and State mandates without a community commitment to their implementation and the costs and manpower needs this commitment would entail. An ordinance should represent community policy concerning stormwater management and should be adopted only after careful study and understanding of requirements for implementation. Technical and administrative detail should be contained in other reference documents which are more subject to modification as needs arise. Manuals should be approved by local government and incorporated by reference in the ordinance if they are to have the force of law.

Technical manuals should present examples in such detail that a design engineer can determine what is generally expected. Several design examples should be given, along with citations of references of additional criteria, with latitude for the engineer to use his imagination and technical judgment. They should suggest and inform rather than limit and prescribe.

The advantages and disadvantages of flexible and specified criteria and standards must be carefully weighed. Ideally, a local program should be sufficiently flexible to encourage an engineer to devise an optimum solution for each problem. To do this, local government must have sufficient qualified people to evaluate each project on a case-by-case basis. Inter-relationships between the existing system and proposed projects will have to be assessed. Many—if not most—smaller communities may not have this capability and uniform requirements may appear to be the only way that objectives can be attained. Yet, these will limit opportunities to realize the most socially acceptable and cost-effective solutions. The trade-offs between the two approaches need to be assessed in light of a community's capability and commitment to administer the ordinance.

The drafting of a stormwater ordinance should be a team effort representing departments of engineering, public works, planning, and legal affairs. Its prospects for implementation are low if it is not acceptable to any of these departments. The ordinance will also affect many different interest groups, and local support necessitates their involvement. Public participation should be integrated into the initial phases when problems and issues are resolved and not limited to the endorsement of the final product.

While model ordinances have their role, circumstances may be quite different than visualized, and local government should be careful to tailor the model ordinance to address its own local conditions, problems, policies, objectives, and state enabling legislation.

No ordinance can cover all possible situations, and provision for the issuance of special use permits adds a degree of flexibility needed. Their use can weaken or destroy the effectiveness of an ordinance when abused. Special use permits should be carefully prescribed with specified procedures to be followed in their administration.

Maintenance of a stormwater system can be a serious problem. The ordinance should state clearly what parts of the system will be maintained by local government and private interests and the terms and conditions of such maintenance.

Stormwater ordinances are only as strong as local governments' desire or ability to enforce them. Enforcement of such ordinances has always had a low priority. Part of the problem arises from imbalance in emphasis between

establishing programs and making them work once adopted. The assumption that property owners will voluntarily comply is not necessarily well founded. The regulations work well when officials give sufficient thought as to how they are likely to be avoided and then work to close loopholes. They do not work well when they are elaborate and require the exercise of discretion in the face of strong developer and property-owner opposition. Administrative remedies may prove to be far more effective than litigation. The withholding of a permit or refusal to take action on one matter until there is compliance on another can be very effective. Field inspection is of critical importance to enforcement. To reduce cost, some cities have adopted random spot checking with heavy fines for violations. This procedure can encourage self-maintenance by owners, reduce the number of inspections, and raise funds for program administration.

Finally, the regulatory provisions dealing with drainage and detention, flood plain management, erosion and sedimentation, and stormwater quality control should be combined in a unified urban stormwater management program. Each is related to the other, and they cannot be addressed adequately if separated. Unfortunately, state enabling legislation does not generally reflect this need. Inadequate enabling legislation is generally a limiting factor in the integration of local stormwater programs. Unless a local unit of government functions under a special grant of power from its legislature, it must depend upon specific state law to exercise the authority it desires. Local jurisdictions considering the adoption of stormwater ordinances should first determine whether existing legislation is adequate.

Stormwater ordinances should be cross-referenced to and integrated with other types of development regulations such as zoning and subdivision ordinances. Flood-hazard area regulations, in particular, should be integrated and coordinated with other land-use regulations. A convenient way to do this is to establish flood hazard "overlay zones." Development in such zones must conform to both the regulations of the conventional zoning district and to the special regulations applicable to the zones of the flood-hazard maps. Drainage ordinances may be cross-referenced to local subdivision ordinances by: (1) Including flood contour elevation information on all development plans; (2) including a requirement in subdivision ordinances that suitable easements be given where subdivisions are crossed by a watercourse or drainageway; (3) tying soil-erosion and sedimentation-control regulations into the subdivision plat approval procedure; and (4) by clarifying and describing drainage improvements required under subdivision ordinances and enabling statutes by reference to a flood- and erosion-control handbook or manual.

The question of cost allocation is important. Costs to meet additional drainage needs in developed areas may be imposed through special assessments or establishment of local service districts. Zoning and subdivision ordinances can be used for cost allocation in areas under development. Courts have generally held that developers can be required to bear the full cost of on-site improvements constructed for the sole benefit of the proposed development. Explicit enabling legislation is needed to uphold a requirement that developers provide funds to local government for the construction of such facilities in lieu of direct construction by the developer. The key issue is the statutory basis for cost allocation.

Conclusions and Recommendations

1. The four areas of urban stormwater management—drainage and detention, flood plain management, erosion and sedimentation control, and stormwater pollution control—tend to be dealt with on an individual basis. They should be addressed as a whole within a unified stormwater management program and integrated with zoning and subdivision ordinances and land-use planning. Every community should have such a comprehensive stormwater-management program.

2. Many ordinances pertaining to urban stormwater management are being adopted without a community commitment to their implementation and the costs and manpower needs this commitment would entail. Adoption of an ordinance is not an end in itself. Additional emphasis must be given to the commitment of the resources required for implementation and enforcement before an ordinance is adopted.

3. Ordinances, in general, should be concerned with policy and budgetary matters, not engineering criteria, design standards, or administrative detail. They should serve as policy statements and the technical and administrative detail should be contained in other reference documents more amenable to updating and change.

4. Local governments considering the adoption of an ordinance should first determine whether state enabling legislation is adequate.

5. The drafting of ordinances should be carried out by an interdisciplinary team representing all departments that will play a significant role in solving local stormwater management problems. Local support of ordinances necessitates involvement of all interest groups in the area to be served. Public participation should be integrated into the initial phases and not be limited to review and endorsement of the final products.

6. Model ordinances and ordinances borrowed from other communities must be carefully evaluated by local government to tailor these to local goals, objectives, and problems.

7. On-site detention is still subject to debate. Further research is needed on the legal, maintenance, and hydrologic aspects of detention facilities. Local governments should go into detention programs only after careful consideration of the total commitment required.

8. Most small communities have neither the resources nor the knowledge required for effective stormwater management. There is need for the development of informational packets on urban stormwater management for smaller communities. These should provide detailed, step-by-step guidance for the design of local programs. City engineers and planners should be much better trained in the tools and techniques of stormwater management. New technology should be diffused throughout the professions that are concerned with stormwater. The technology should be effective and make sense economically so that it will, in fact, be adopted.

9. Many larger cities also appear to have great difficulty in mounting effective stormwater-management programs. More attention should be given to the political and other constraints involved.

10. The most significant problem associated with flood plain management at the local level has been the lack of monitoring to determine compliance with commitments under the Federal Flood Insurance Program relative to the

adoption and enforcement of land-use controls in flood-hazard areas.

11. Many local governments do not have the planning and management capability to carry out their obligations under the Flood Insurance Program and most states have not moved to provide needed technical assistance and institutional support. State government should carefully examine the need for supportive services in this area.

12. Failure of public agencies to forcefully administer sediment-control programs, the unwillingness of some local governments to assume this responsibility, and limited regulatory staffs at state and local levels have been the principal problems in the four southeastern states with erosion- and sedimentation-control legislation.

13. There is reason to believe that developers and contractors might be more supportive of erosion- and sedimentation-control programs if they recognized that compliance can be beneficial to them as well as to the community at large. Intensified education in this area is indicated.

14. While there is general agreement that certain land-use practices enhance water quality, there is little quantifiable information available as to the effectiveness of practices in reducing pollution from urban stormwater runoff, the effects on receiving waters, and the benefits to be gained through reduction of pollution from this source. First-generation 208 studies have not met this need. Proposed USEPA and USGS investigations are expected to contribute substantial new information. Continued research is strongly encouraged.

15. Investigations under the 208 program tend to suggest that urban streams, in general, suffer severe biological degradation attributable to surface runoff, leaking sewers, unauthorized point source discharges, solid wastes, erosion, and sedimentation. A more rigorous enforcement of existing laws and ordinances pertaining to many of these sources would go far toward remedying the urban pollution problem. Cities should be encouraged to undertake the monitoring and data collection needed to determine the source and magnitude of urban water-quality problems so that corrective actions can be taken.

16. Florida has initiated the region's first statewide permitting program for discharges from drainage systems. This should be followed closely to determine its efficacy and potential value to other states.

17. Local government must realize its primary role in stormwater management (SWM). Public works agencies should be encouraged to include SWM in their scope of responsibilities and advocate responsible total programs before their decision-making boards.

18. More research is needed on the causes of urban nonpoint pollution. However, it is inevitable that there will never be enough money available for structural solutions across the land, outside of large concentrated urban areas. Therefore, state and local governments should act now to do as much as possible with the tools and techniques already available.

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SAMPLING TO CHARACTERIZE STREAM PLUMES

By Christopher C. Clarkson,[1] James W. Male,[2] Associate Members, and Donald Dean Adrian,[3] M. ASCE

INTRODUCTION

Problem Statement.—The design of a program for obtaining representative samples from the cross section of a stream may require considerable knowledge of the mixing characteristics of the stream. These characteristics are usually unknown, necessitating assumptions about the dispersion of pollutants in the stream cross section. Often the unrealistic assumption of complete mixing of a pollutant is assumed for convenience. This paper will present a rationale and a format for sampling in a cross section through development of a procedure that requires a small number of samples to characterize a plume in a stream. Guidelines are developed for the number of grab samples required to characterize the plume, and the potential is shown for obtaining representative samples without the benefit of detailed information on the stream.

Background.—It is common to find that sampling programs are designed under the assumption that the cross section of a stream is homogeneous (2,12,15), although it is commonly recognized that this simplifying assumption is not warranted in many cases. Many authors (4,5,8,9,10,11,13,14,18,22) have investigated the phenomenon of mixing in a stream and have presented various empirical and analytical methods for characterizing longitudinal, vertical, and transverse mixing. If one follows their examples, presumably, samples taken anywhere in a stream cross section that is completely mixed will be representative of river quality in that area, and sampling need not be extensive. If complete-mixing conditions do not exist, then one must either find the most representative point

[1]Water Resources Engr., Camp Dresser and Mckee, Inc., Annandale, Va. 22003.
[2]Assoc. Prof., Dept. of Civ. Engrg., Univ. of Massachusetts, Amherst, Mass. 01003.
[3]Prof., Dept. of Civ. Engrg., Univ. of Massachusetts, Amherst, Mass. 01003.

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at which to sample in the cross section, or one must take several samples in the cross section to estimate mean concentrations. Kittrell (15) suggests sampling at the quarter points, or failing this, at midstream. Based on preliminary examination of Schleeweis' (21) data taken in a cross section of the Connecticut River downstream from two sewage treatment plants, Sanders (17) too suggests sampling at the quarter points.

Sanders, et al. (18) also studied the distance a pollutant must travel in a stream before it can be assumed to be completely mixed (the mixing length). It is probable that several discharges may enter a stream within the mixing length of a given plume. As the discharges to a stream may occur almost anywhere and will be of variable quality and rate of flow, it is unlikely that a reach can be found which is homogeneous in all respects. Given this circumstance, it is desirable to be able to estimate water quality characteristics at a cross section without having to either: (1) Assume complete mixing; or (2) collect a large number of samples.

This paper will describe a method by which grab samples taken in the transect of a stream may be used to describe several properties of a plume contained in that stream. By doing so, the average water quality in the stream section can be determined without having to assume complete mixing. The following analysis consists of two parts; the first is directed toward the characteristics of a plume and the second considers the plume as a part of the entire stream. Statistical relationships descriptive of the normal distribution will be used to examine a continuous discharge, and a simulation procedure will be presented that employs a least-squares gradient search algorithm to characterize the cross section of a steady-state plume and to estimate mass flux in the plume. The least-squares procedure is applied to both simulated and measured data. The procedure enables determination of the minimum number of samples required from the cross section of a plume to characterize the plume.

The second part of the paper will address the entire stream cross section, of which the plume cross section is a part. Since the location and the extent of dispersion of the plume are not known prior to sampling, enough samples must be taken in the stream cross section to allow detection and characterization of the plume. The negative binomial distribution is examined as a means by which to determine the number of samples from the stream cross section necessary to determine characteristics of a plume contained within that section.

To clarify the use of the word "sample," the following distinctions are made: The water in a single bottle will be referred to as a grab sample while a set of grab samples taken at the same depth in the cross section will be referred to as a transect sample. For simplicity, uniform concentration of the plume in the vertical will be assumed. In addition, it will be assumed that grab samples are taken horizontally across the transect at equally spaced intervals.

Theory

If not influenced by channel boundaries or severe turbulence, the steady-state discharge to a stream from a point source outfall forms a plume which disperses laterally and vertically in a fashion which may be characterized as a normal or Gaussian distribution (4,6,19,20). There are three basic characteristics of a plume so formed which are of interest: (1) The longitudinal line traced by

the center of concentration; (2) the extent to which the plume has become dispersed in the cross section; and (3) the total mass flux of the plume. These three characteristics will be called center, spread, and flux, respectively, and they will be examined in a two-dimensional transect in the stream. Unless otherwise indicated, all consideration of spread will be in reference to lateral dispersion only. The terms center, spread, and flux will be used to distinguish among characteristics of the plume itself for the necessary calculation and description of a mean and standard deviation for each of these characteristics. Center and spread in a plume are analogous to the mean and the standard deviation, respectively, of a normal density distribution.

For the case of a single, undisturbed, steady-state point discharge to the center of a stream, the concentrations of several grab samples taken at the same depth but at different points in the cross section appear as shown in Fig. 1. The figure depicts a typical transect sample, accompanied by a fitted normal curve.

It will be assumed in this paper that before its edges have reached the stream bank, the lateral distribution of a plume may be considered to be Gaussian. In the Gaussian distribution, the abscissa represents the attribute being considered and the corresponding ordinate represents the frequency of the magnitude of the attribute. Making an analogy (Fig. 1), the dye concentrations may be represented on the ordinate and lateral position on the abscissa.

A general expression for the ordinates of a normal distribution is given by:

$$y_i = y(x_i, \bar{x}, s) = \left(\frac{1}{s\sqrt{2\pi}}\right) \exp\left[-\frac{1}{2}\left(\frac{x_i - x}{s}\right)^2\right] \quad \ldots\ldots\ldots\ldots (1)$$

in which $\bar{x}$ and s = the population mean and standard deviation, respectively; and x_i = values of the parameter of interest.

A plot of y_i versus x_i yields a curve of unit area. An analogous expression which may be used to fit a normal curve to a histogram is given by Dixon (7) as:

$$y_i = \left(\frac{IM}{s}\right)\left(\frac{1}{\sqrt{2\pi}}\right) \exp\left[-\frac{1}{2}\left(\frac{x_i - \bar{x}}{s}\right)^2\right] \quad \ldots\ldots\ldots\ldots\ldots (2)$$

in which M = the number of cases observed; I = length of class interval used to draw the histogram; and IM/s represents the height of curve for a histogram of total area IM. The value IM therefore represents a scale factor needed to describe a curve with other than unit area. In this application, M is analogous to a summation of concentrations measured in a transect sample from the plume, and I represents the distance between sampling points. It is assumed that all grab samples are equally spaced in the cross section.

In the coordinate system used in reference to a stream, X, Y, and Z represent the longitudinal, lateral, and vertical directions, respectively. Substituting values of Y_i (lateral position in the plume) for x_i (in Eq. 2) on the abscissa yields an expression which may be used to find concentration at a given point in a plume when the center ($\bar{Y}$) and spread (S) of the plume are known:

$$C_i = \left(\frac{IM}{S\sqrt{2\pi}}\right) \exp\left[-\frac{1}{2}\left(\frac{Y_i - \bar{Y}}{S}\right)^2\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which C_i = concentration at a specified point i, (M/L^3); I = distance between sampling points, (L); M = sum of measured concentrations in a transect sample, (M/L^3); S = spread, (L); Y_i = lateral location, (L); and $\bar{Y}$ = center, (L).

Eq. 3 would be an appropriate expression to use in calculating concentrations at various points Y_i in the cross section of a stream, provided that the other parameters are known. It should be noted that Eq. 3 is correctly used to generate concentrations for a set of points which are all at the same depth. If a pollutant is not uniformly mixed vertically, transect samples drawn from different depths will yield unique concentration distribution curves.

Mass flux may be found by considering the stream cross section to be comprised of a number of cells formed by defining C columns across the transect and R rows from the surface to the bottom of the stream. Ignoring velocity variations

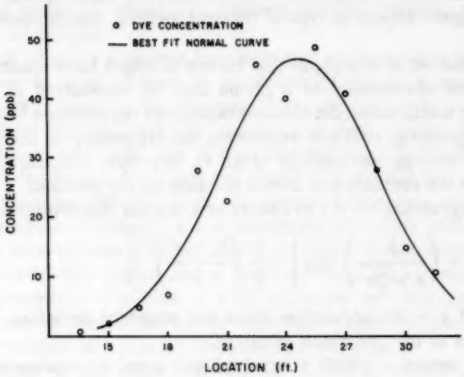

FIG 1.—Dye Concentration Versus Lateral Position from Stream Bank, with Fitted Normal Curve (1 ft = 0.305 m)

in the cross section, the flow q_c in each cell is given by:

$$q_c = \frac{Q}{RC} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

in which Q = stream flow, (L^3/T); R = number of rows, dimensionless; and C = number of columns, dimensionless. Letting j and k be the indices for rows and columns, respectively

$$\text{Flux} = \sum_{j=1}^{R} \sum_{k=1}^{C} (q_c m_{jk}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

in which m_{jk} = concentration in cell jk, (M/L^3).

If there is a vertical concentration distribution, with the flux in each row equal to M

$$\text{Flux} = R(qM) = R\left(\frac{Q}{RC}\right)M = \frac{QM}{C} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

but $C = W/I$ when W = stream width; and I = interval or column width. Therefore

$$\text{Flux} = \frac{QM}{C} = \frac{(IM)Q}{W} = \frac{(IM)(uWH)}{W} = (IM)(uH) \quad \ldots\ldots\ldots\ldots\ldots (7)$$

in which u = average stream velocity, (L/T); and H = stream depth, (L). Thus, Eq. 7 provides a means to determine mass flux from the scale factor IM.

Methodology

Equations were presented in the preceding section to describe relationships among several factors descriptive of the behavior of a pollutant in a stream. The most important concept is the analogy drawn between the normal distribution and the characteristics of a plume. In Eq. 3 for the normal curve, the only parameters which would be known after drawing a transect sample from the cross section are pairs of C_i and Y_i at a given depth, whereas IM, S, and $\bar{Y}$, which are unknown, are needed to reconstruct the plume and to determine mass flux.

To find these unknowns, the criterion of minimizing the sum of squared differences (SSD) has been used to obtain the normal curve that best fits hypothetical concentration data and thus, to obtain the best estimates of IM, S, and $\bar{Y}$. The sum of squared differences is found by:

$$\text{SSD} = (Cm_i - Cp_i)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

in which Cm_i = a measured or simulation value for concentration; and Cp_i = a concentration predicted by Eq. 3.

Measured or Simulated Concentrations, Cm_i.—Values of Cm_i were determined in two basic ways: (1) By measurement; and (2) by simulation. Simulated values were generated using two different approaches.

The first simulation method for calculating a set of values of Cm_i used Eq. 3 for which values of IM, S, and $\bar{Y}$ were specified. Values of Y_i were selected and the corresponding values of Cm_i were calculated. The method was used by first assuming no error and then adding to Cm_i a random error ranging from -10%–$+10\%$.

The second simulation method used Clearly's (5) steady-state analytical solution to the three-dimensional, advection and dispersion, partial differential equation (4). This will be called the 3D-SS solution. Dispersion coefficients for the steady-state case were obtained using Fischer's (8,9) expressions, and dimensions were specified that approximated the Connecticut River in Massachusetts. A complete description of the equation and input parameters is found in Clarkson (3).

The third method for determining values of Cm_i involved the use of measured field data. Steady-state dye tracer studies were performed on a channelized section of the Mill River in Northampton, Mass. A fluorescent dye was used to establish a steady-state plume in the stream, from which transect samples were drawn below the point of dye injection.

Grab samples were taken in a three dimensional array representing different longitudinal locations (different transects downstream) and lateral and vertical

points in each transect. A description of the sampling equipment and procedure appears in Ref. 3.

Predicted Concentrations (Cp_i) and Least Squares Curve Fitting Procedure.—With IM, S, and $\bar{Y}$ specified, values of Y_i may be substituted into Eq. 3 to calculate corresponding values of Cp_i (C_i in Eq. 3). By systematically altering values of IM, S, and $\bar{Y}$, many sets of values of Cp_i may be calculated. That set of values of Cp_i which results in the smallest SSD when compared with corresponding values of Cm_i represents the normal curve which can be most closely forced to fit values of Cm_i.

To find the best fit normal curve, an initial guess is specified for each of the three unknowns, IM, S, and $\bar{Y}$, and an increment or step size is specified by which each of these will be changed. Twenty-seven points are generated each representing a different combination of IM, S, and $\bar{Y}$. Values of Y_i previously selected are substituted into Eq. 3 to calculate a corresponding set of predicted values of Cp_i at each of the twenty-seven points. Eq. 8 is then applied at each point to calculate an SSD, and the twenty-seven SSDs are systematically compared to select the smallest. The values of IM, S, and $\bar{Y}$ associated with this point become a new starting point and the procedure is repeated. Repetition continues until a minimum SSD has been found. The associated values of IM, S, and $\bar{Y}$ so selected may be taken as the solutions, for when they are substituted into Eq. 3, the values of Cp_i calculated fall on the normal curve that best fits (in a least squares sense) the set of values of Cm_i. The accuracy of these solutions will be determined in part by the initial values and step sizes specified. In general, different starting points will result in solutions which differ, but which do not differ appreciably, especially when the procedure is programmed to allow for a steadily decreasing step length. The risk of obtaining a solution at a local rather than a global minimum SSD is greatly reduced by repeating the procedure with different initial values of IM, S, and $\bar{Y}$. If the resultant sets of solutions agree, then a global minimum has probably been found. In this application, the range of possible values for S and $\bar{Y}$ is effectively delimited by stream dimensions.

Results

Gaussian Case.—The gradient search curve fitting procedure was first tested using the Gaussian case, with and without error, and with specified values for S, $\bar{Y}$, and IM, to verify its accuracy and precision. To simplify the analysis, and since flux and the scale factor are related by a constant, flux will be considered the unknown and the scale factor will not be reported directly:

$$\text{Flux} = (IM)(uH)\left(\frac{28.317}{1{,}000}\right), \left(\frac{\text{mg}}{\text{s}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Results reported in this and the following subsection were developed as follows: Simulations were made for several numbers (n) of grab samples in each transect sample. For a given value of n, the curve fitting procedure was repeated N times to generate N values for each of the three unknowns S, $\bar{Y}$, and flux. The N values of center, as an example, were then compiled to calculate a mean and standard deviation for a given n. In addition, 99% confidence intervals were determined.

The results of Gaussian simulation with error ($-10\% \leq$ Error $\leq 10\%$) are presented in Table 1. For purposes of comparison, the results with no error added are presented in the left hand portion of Table 2. In Col. 6 of Table 1, the extreme of the 99% confidence interval from the mean is listed as a percentage of the mean. The column "deviation from known" gives the greatest percentage deviation in the confidence interval from the known value. This tabulation is repeated for each value of n, for each of the unknowns.

For flux in Table 1, as an example, the information may be interpreted to

TABLE 1.—Plume Simulation Experiments for Gaussian Case with Error Added

n (1)	N (2)	Mean (3)	Standard deviation (4)	99% Confidence interval (5)	Deviation from mean, as a percentage (6)	Deviation from known, as a percentage (7)	Total flux as a percentage (8)
				(*a*) Spread			
2	10	75.29	13.0842	61.84–88.74	17.86	47.22	
4	10	60.13	1.1195	58.98–61.28	1.91	1.66	
6	10	60.09	2.0517	59.34–60.84	1.25	−1.56	
8	10	60.38	1.4485	58.89–61.87	2.47	2.64	
10	10	60.16	1.7671	58.34–61.98	3.03	−3.22	
				(*b*) Center			
2	10	408.05	26.2709	381.05–435.05	6.62	8.76	
4	10	401.13	2.1538	398.92–403.34	0.55	0.84	
6	10	399.14	2.2758	396.80–401.48	0.59	−0.80	
8	10	400.03	2.4522	397.51–402.55	0.63	0.64	
10	10	400.56	1.4927	399.03–402.09	0.38	0.52	
				(*c*) Flux			
2	10	147.87	22.0582	125.20–170.54	15.33	−15.91	99.31
4	10	152.04	5.7959	146.08–158.00	3.92	6.12	102.12
6	10	148.27	3.9434	144.22–152.32	2.73	−3.14	99.58
8	10	148.59	3.5710	144.92–152.26	2.47	−2.67	99.80
10	10	147.99	3.2691	144.63–151.35	2.27	−2.68	99.80

Note: $S = 60.2791$ ft; $\bar{Y} = 400$ ft; $G = 148.89$ mg/s; $X = 500$ ft; and 1 ft = 0.305 m.

indicate that the average flux for ten transect samples of four grab samples each is 152.04 mg/s with a standard deviation of 5.80 mg/s. The 99% confidence interval suggests that for 99 out of 100 samples, i.e., if $N = 100$, the average flux may be expected to lie between 146 mg/s and 158 mg/s. The greatest range of the confidence limits from actual flux is about −16%, for $n = 2$. The last column shows the percent of total flux (the experimental tracer injection rate, G) determined.

Because the expression for the ordinates of a normal distribution (Eq. 3)

was used to generate both simulated and predicted values treated in the gradient search, it is to be expected that the least squares line so obtained should fit well. For the case in which no error was added (Table 2) the average solutions are excellent and their respective standard deviations, which are quite small to begin with, decrease with increasing n.

When error is added to each value of Cm_i the solutions obtained are still quite good excepting the case of $n = 2$. For $n = 2$, the solutions for center and flux are reasonable although their respective standard deviations are high.

TABLE 2.—Plume Simulation Experiments

Gaussian, No Error[a]					3D-SS, No Error[b,c]				3D-SS, Error Added[b,c]			
n (1)	N (2)	Mean (3)	Standard deviation (4)	Deviation from known, as a percentage (5)	n (6)	Mean (7)	Standard deviation (8)	Deviation from known, as a percentage (9)	n (10)	Mean (11)	Standard deviation (12)	Deviation from known, as a percentage (13)
						(*a*) Spread						
2	1	60.29			2	82.17	15.1223		2	84.24	19.1020	
3	5	60.30	0.0320	0.12	4	51.50	0.3106		4	52.64	1.9943	
4	7	60.28	0.0028	0.00	6	52.40	0.4942		6	53.13	1.6937	
6	4	60.28	0.0001	0.00	8	52.68	0.0201		8	52.78	1.2292	
10	3	60.28	0.0000	0.00	10	52.69	0.0022		10	52.50	1.1416	
						(*b*) Center						
2	1	399.99			2	400.62	48.0306	12.50	2	425.38	46.2888	18.24
3	5	400.00	0.0351	0.01	4	400.51	1.4189	0.49	4	400.15	1.5878	0.45
4	7	400.00	0.0053	0.00	6	400.09	0.4001	0.13	6	399.91	1.8058	−0.49
6	4	400.00	0.0010	0.00	8	400.01	0.0077	0.01	8	399.43	1.5346	−0.54
10	3	400.00	0.0000	0.00	10	400.00	0.0011	0.00	10	399.25	1.5340	−0.58
						(*c*) Flux						
2	1	148.91			2	109.05	34.8173	−51.15	2	132.42	44.4531	−43.61
3	5	148.92	0.0472	0.07	4	146.54	2.3286	−3.90	4	149.85	6.9812	−4.88
4	7	148.88	0.0000	−0.03	6	148.21	0.7964	−1.74	6	147.24	5.3400	−5.50
6	4	148.88	0.0018	−0.01	8	148.30	0.0245	−1.15	8	151.77	3.2625	3.41
10	3	148.88	0.0000	−0.01	10	148.32	0.0033	−1.12	10	149.31	4.5229	−3.56

[a] $S = 60.2791$ ft, $Y = 400$ ft, $G = 148.89$ mg/s, $X = 500$ ft.
[b] $Y = 400$ ft, $G = 150$ mg/s, $X = 500$ ft.
[c] $N = 10$ for all 3D-SS experiments; 1 ft = 0.305 m.

For spread, both the average value and its associated standard deviation are high. The standard deviation for flux shows a decreasing trend for increasing n; such a trend is not as certain for center and spread.

Three Dimensional Steady-State Case.—In this phase, the 3D-SS rather than the Gaussian expression was used to generate values of Cm_i. Both center and flux are specified beforehand and may be used to verify results. Spread is not known. Table 2, which shows the results of simulations with 3D-SS, is best compared with the Gaussian no error case. The standard deviation for

each of the three unknowns drops steadily with increasing n, while the known values for center and flux have been nicely determined for all n excepting flux when $n = 2$. Spread itself is not known, however, the search procedure quickly approaches a constant value, for $n = 4$ or greater.

In both the Gaussian and 3D-SS cases, the flux and center of concentration are correctly determined while there is some discrepancy in the apparent extent to which the plume has expanded laterally. The discrepancy is explained by the fact that the tails of a normal distribution theoretically extend to plus and minus infinity. The 3D-SS case, however, is limited by the banks of the stream.

The standard deviation of a Gaussian distribution delimits a range above and below the mean within which 68.26% of the probability density lies. In this application, one standard deviation using the Gaussian expression indicates the range within which 68% of the dye mass is found. Since it is a normal curve which the gradient search forces through values of Cm_i generated by 3D-SS, the value for spread (which is a measure of standard deviation for the dye mass as a whole) would still imply a range within which 68% of dye mass is found. Apparently then, spread is more correctly interpreted as a range within which a fixed proportion of mass is found than as a measure of the rate of lateral dispersion as considered by Diachishin (6), Holley (14), and Sayre and Chang (20).

The right hand portion of Table 2 shows the 3D-SS case to which random error has been added. In comparing the two 3D-SS cases it should become apparent that, despite the presence of error, the gradient search procedure still determines the three unknowns quite well, except when $n = 2$.

Several experiments were conducted which are more fully described in Clarkson (3) and Adrian et al. (1). In these studies the longitudinal distance between injection and sampling (X), the lateral injection point, and the total mass flux (G) were varied to determine their effect on the results generated by the procedure. The results correspond closely with those that would be expected. Some problems were encountered, however, when the longitudinal distance (X) reached and exceeded 4,500 (1,372) and when the point of injection was brought to within 50 ft (15 m) of the bank.

The amount of computer time required for solution convergence varied with the random starting point used for the systematic selection of values of Y_i, and with the size of the transect sample. While the procedure would work for several values of n (values of $n = 2$, 3, 4, 6, 8, and 10 were tested), in general, much more computer time was required for a transect sample of $n = 2$ or $n = 3$ than for a sample of larger size.

The ability to obtain a good fit depends not only upon the initial values of spread, center, and flux specified for the search, but also upon the number of sampling points selected. It is apparent that satisfactory results may not be expected for $n = 2$ or for $n = 3$, but that at least four grab samples will be required from the plume to have reasonable confidence in the results of the procedure.

Field Data Case.—Steady-state dye tracer studies were performed in a stream to collect field data that could be used to test the curve fitting procedure mentioned in the preceeding sections. A typical dye concentration distribution and stream bottom profile are shown in Fig. 2. The data depicted in Fig. 2 may be viewed as six transect samples, each taken at a different depth. By inspection, the

dye appears to be normally distributed from side to side, and roughly uniform in concentration from surface to bottom. When the data from a single row or transect sample are plotted, as in Fig. 1, a characteristic Gaussian-like shape is observed. The data in Fig. 1 were obtained at a depth of 1.5 ft (.46 m) and at a distance of 186 ft (56.7 m) from the injection point. The lateral position of the injection point was 22.7 ft (6.9 m).

Using the gradient search procedure, field measurements were substituted into Eq. 8 for Cm_i, and Eq. 3 was used for values of Cp_i. As before, starting values for S, $\bar{Y}$, and IM were substituted into Eq. 3 to initiate the search. The results for the third row of the illustrative case are shown in Table 3.

A complete analysis of the transect is found in Table 4. The transect sample

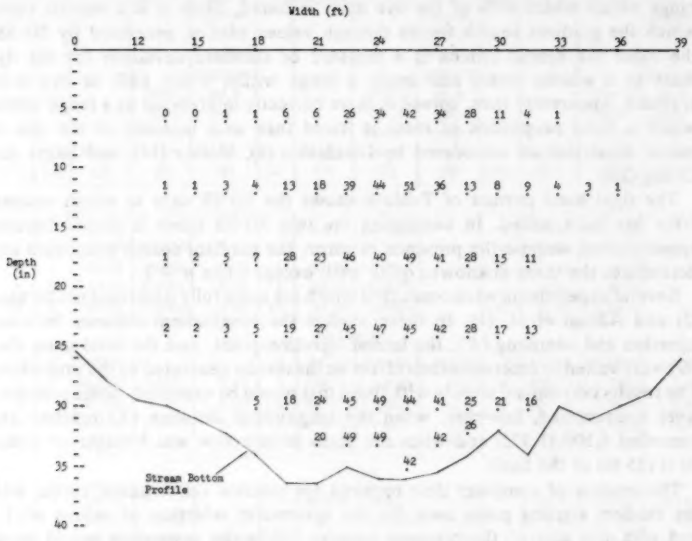

FIG. 2.—Dye Concentrations for Typical Transect, in parts per billion (1 ft = 0.305 m)

closest to the bottom was not analyzed because its component grab samples were not all taken at the same depth.

In general, the search procedure worked well with field data although there were some transect samples which were apparently not normally distributed, for which the procedure would fail to converge despite running for a considerable period of time.

The most obvious problem with the search procedure lies in its failure to determine mass flux accurately. In general, the predicted values were low. This problem can be attributed to the fact that ideal conditions were assumed in the procedure: Uniform prismatic channel, constant uniform velocity, and uniform concentrations in the vertical.

To partially compensate for nonideal conditions in the stream, velocity measurements were reexamined and a second value for average velocity was calculated using only that portion of the cross section in which tracer was found. A correction factor of 1.28 was derived, and when applied to the results, improved the predicted values for flux. The corrected values appear in Table 4.

Sample Size Requirements in Stream Cross Section

The question of the number of grab samples required from a plume to characterize the plume was addressed earlier. In this section, analysis will address the sample size required from the cross section of the stream when the location of a plume is not known.

TABLE 3.—Comparison of Measured Concentrations with Concentrations of Normal Curve, in parts per billion

Y_i, in feet (1)	Cm_i (measured) (2)	Cp_i (fitted) (3)
13.5	1.00	0.74
15	2.00	2.10
16.5	5.00	5.13
18	7.00	10.79
19.5	28.00	19.48
21	23.00	30.26
22.5	46.00	40.43
24	40.00	46.44
25.5	49.00	45.88
27	41.00	38.98
28.5	28.00	28.50
30	15.00	17.89
31.5	11.00	9.67
Total	296.00	296.29

Note: Depth = 1.5 ft (0.46 m).

Taking the simple case of a single dye cloud or plume, a plane drawn perpendicular to the direction of flow may be pictured as two sets, i.e., one, the area of the plume which is a subset of the second, the total area of the cross section. If a single horizontal line in the transect is examined, the width w of the plume is a subset of the stream width W. If each location in W either does or does not contain dye (disregarding relative concentration, or concentration distribution), then each grab sample drawn may be considered to be a Bernoulli experiment, and a set of samples drawn a set of Bernoulli trials where the probability of success p of drawing a grab sample containing dye is given by:

$$p = \frac{w}{W} \quad \ldots\ldots\ldots\

The negative binomial distribution may be used to analyze Bernoulli trials. The negative binomial distribution treats the case in which Bernoulli trials are repeated until a given number of successes are observed (16). The total number of trials required is random and is equal to the number of successes and failures. Letting S_r denote the number of failures encountered prior to the rth success:

$$P(S_r = j) = (-1)^j \binom{-r}{j} p^r q^j = \binom{r+j-1}{j} p^{r-1} q^j p \quad \ldots\ldots\ldots\ldots (11)$$

in which p = the probability of success; q = one minus p; and j = the number of failures prior to the rth success. The mean and variance of S_r are given by:

$$E(S_r) = \frac{rq}{p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$\text{var}\,(S_r) = \frac{rq}{p^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Finally, let T denote the number of trials required to obtain r successes of

TABLE 4.—Summary Tabulations for Illustrative Cross Section

Depth, in feet (1)	Center, in feet (2)	Spread, in feet (3)	SSD (4)	Corrected flux,* as a percentage (5)
0.5	25.62	2.82	64.04	56.37
1.0	24.63	2.82	163.70	67.15
1.5	24.63	3.86	236.48	88.14
2.0	24.77	3.69	74.13	87.17
2.5	24.87	3.75	147.90	87.17
Average vertical concentration	24.88	3.43	73.03	76.87

*Percentage of known flux (10.29 mg/s) derived from transect sample.
Note: 1 ft = 0.305 m.

probability p, in which S_r is as defined earlier. Then:

$$P(T = j + r) = \binom{r-1}{j} p^r q^j, \quad \text{for} \quad j = 0, 1, 2, 3 \ldots \quad \ldots\ldots\ldots\ldots (14)$$

The expected value of T is:

$$E(T) = E(S_r) + r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$$\text{Since} \quad E(S_r) = \frac{rq}{p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$$E(T) = \frac{rq}{p} + r = r\left(\frac{q}{p} + 1\right) = r\left(\frac{q+p}{p}\right) = \frac{r}{p} \quad \ldots\ldots\ldots\ldots (17)$$

Eq. 17 may be used to determine the number of samples (T) required in the cross section to obtain r successes when the probability of success is p. This relationship, shown in the right hand side of Fig. 3, may be used in several ways, e.g., if twenty grab samples are taken in the cross section and six of them in a cluster contain some substance of interest, then it may be surmised that a plume carrying the substance covers about 30% of the cross section. If it is known that there is a plume in a stream with probability $p = 0.2$ at a transect and it is desired to have four grab samples from which to estimate center, spread, and flux, twenty grab samples should be taken in the cross section. Using Eq. 17, $E(T) = r/p = 4/2 = 20$.

Costs and availability of resources must also be taken into account in designing a sampling program. Assuming that costs vary directly with the number of samples to be processed, one might conceivably generate a cost function related to measurement of each parameter of interest. Adding a cost function, as shown in the left hand side of Fig. 3 provides a simple method to relate costs with the sample size considerations mentioned above. If \$1,000 can be allocated

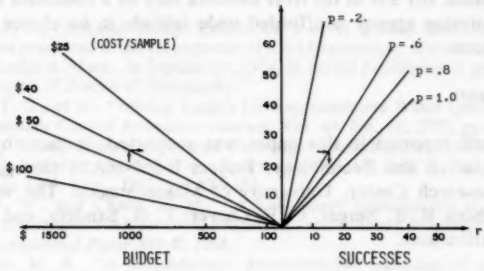

FIG. 3.—Relationship between Cost of Sampling, Number of Trials T, and Likelihood of Obtaining r Successes at Various Levels of Probability, P

to a sampling program and it costs \$40 to collect and analyze each grab sample, 25 samples may be taken. If the relationship of p with distance X is known from previous sampling experience in relation to a particular outfall, the right-hand side of Fig. 3 could be entered with $T = 25$ to see how many successes r would be obtained at a given p.

Conclusions

This paper offers new perspectives on a problem which should be addressed in the design of a river basin monitoring program: How to go about taking samples in a stream cross section. By combining plume simulation with a gradient search curve fitting procedure: (1) A means is provided by which to characterize a pollutant plume by finding its mass flux, center of concentration and standard deviation—a measure of lateral dispersion; and (2) the number of grab samples is determined which are needed from the cross section of the plume to estimate these characteristics. Findings indicate that as few as four grab samples from

the cross section of the plume are sufficient to determine the three properties considered.

The plume characterizing procedure analyzes grab samples taken directly from the plume. If the lateral position of a pollutant in a stream is not known, sampling will have to be done in the entire cross section to be sure of drawing samples from the plume. The negative binomial distribution offers some insight into determining how many grab samples to draw from the entire cross section to be able to characterize a constituent plume. A consideration of cost factors is included in the analysis.

The procedure for characterizing a plume was tested with experimental data. The results show that cross-sectional samples which might normally be used only to determine a mean concentration may in fact yield considerably more useful information on the water quality of a stream.

The ability to extract useful information from grab samples taken in a cross section indicates that monitoring agencies need not feel compelled to find actual regions of complete mixing in which to sample, nor need they feel compelled to operate under the assumption of complete lateral mixing. If not held to these constraints, any site in the river network may be a candidate for sampling, and the monitoring agency is afforded wide latitude in its choice of sampling station locations.

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Appendix II.—Notation

The following symbols are used in this paper:

C = number of cell columns;
C_i = concentration of point Y_i;
Cm_i = measured concentration at Y_i;
Cp_i = predicted concentration at Y_i;
G = flux or tracer injection rate;
H = stream depth;
I = histogram class interval or distance between equally spaced sampling points;
M = number of cases observed or summation of concentrations measured in sample from plume;
m_{jk} = concentration in cell jk;

N = number of transect sample repetitions;
n = number of grab samples in each transect sample;
p = probability of sampling from plume;
Q = stream flow;
q = probability of not sampling from plume;
q_c = flow in stream cell;
R = number of cell rows;
r = number of samples from plume;
t = number of samples from plume;
S = spread of plume;
S_r = number of failures prior to rth success;
s = standard deviation;
T = number of trials needed to obtain r successes;
u = average stream velocity;
W = width of stream;
w = width of plume;
X = distance downstream from injection point;
$\bar{x}$ = mean;
$\bar{Y}$ = center of plume;
Y_t = lateral position in plume; and
y_t = ordinate of normal distribution given abscissa value x_t.

JOURNAL OF THE WATER RESOURCES PLANNING AND MANAGEMENT DIVISION

GROWTH CONCERNS DEFEAT A COUNTY WATER ISSUE

By Charles H. Lawrance,[1] F. ASCE

INTRODUCTION

The recent decision by Santa Barbara County, Calif., concerning the importation of northern California water from the State Water Project (SWP), required public consideration not only of fairly complex technical data, but also of controversial socio-economic matters. In effect, the county stood at the crossroads and chose between: (1) Importing costly, albeit affordable, high quality supplemental water from the California Aqueduct, which has an availability that might stimulate growth undesirably; and (2) pursuing local, lower yield, water resources alternatives exclusively, while relying on local growth management and consumer conservation to limit demand. Various external pressures added to the urgency and complexity of the decision, and its deliberations.

This paper presents an overview of the technical, socio-economic, environmental, and political considerations that had a bearing in the county's decision. The purpose of the paper is to indicate how both traditional and innovative water supply alternatives were viewed by water purveyors, elected officials, various organizations, and the voting public.

BACKGROUND

Santa Barbara County lies about 52 miles (84 km) west of the metropolitan Los Angeles area (see Fig. 1). The south coast of the county contains several urban communities, but north of the Santa Ynez Mountains, there are only scattered communities, including Vandenberg Air Force Base. Most of the county

[1]Principal Engr., James M. Montgomery, Consulting Engrs., Inc., Irvine, Calif.; formerly Engr.-Mgr., Santa Barbara County Water Agency, Santa Barbara, Calif.

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is mountainous and lies within the Los Padres National Forest (see Fig. 2). In addition to two municipally-owned upstream reservoirs on the Santa Ynez River, there is a much larger reservoir (Cachuma) on this river and another (Twitchell) on the Cuyama River, both of which were sponsored by the Santa Barbara County Water Agency, a county-wide special district, and constructed by the United States Bureau of Reclamation. Groundwater continues to be the primary supply source of most of the county's water producers.

In view of limitations in local supplies, county water planners realized two decades ago that under normal growth, supplemental water would eventually be required. Thus, the county, acting through its Flood Control and Water Conservation District, contracted for imported water, starting in 1980, from

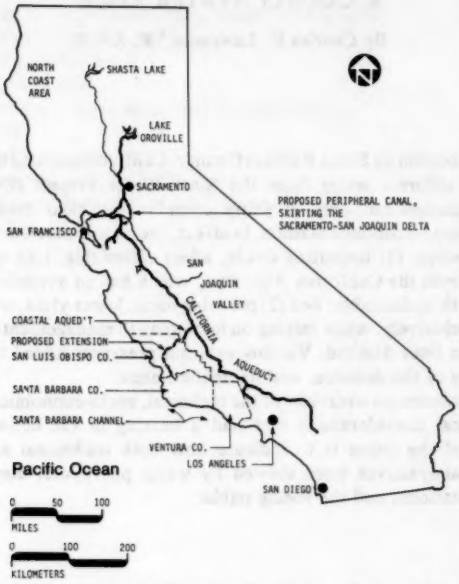

FIG. 1.—California Coast

the State Department of Water Resources (DWR), with deliveries beginning at 1,200 acre-ft/yr (1.48 ha-m^3/yr), and building up to a maximum entitlement of 57,700 acre-ft/yr (71.2 ha-m^3/yr) by 1980.

At the local level, water districts followed traditional planning procedures in arranging for sufficient water supply in advance of projected demands. The public took these matters for granted, but became increasingly troubled by air pollution and some of the other adverse effects of urbanization. Thus, the California electorate generally awakened to the period of environmental awareness which began in the late 1960s.

Santa Barbarans, in particular, had been aroused by the 1969 oil well blowout

in the Santa Barbara Channel. Growing numbers of these south coast residents became concerned that uncontrolled urbanization would damage the unique ambience of the local environment, and that providing water supply to offset imminent or existing deficits would only ensure increased urbanization. After the county's consulting engineer rendered a report on the SWP and alternative supplies (1), the composition of the governing bodies of some south coast water districts began to change, reflecting this controversy. Water moratoria were declared by three districts in 1972–1973, because deficits in firm supply became apparent and various south coast water entities sponsored a separate engineering study on water alternatives for the south coast (37). The report intentionally limited its considerations for additional supply to the south coast, excluding consideration of jurisdicational, legal, and institutional matters. Of

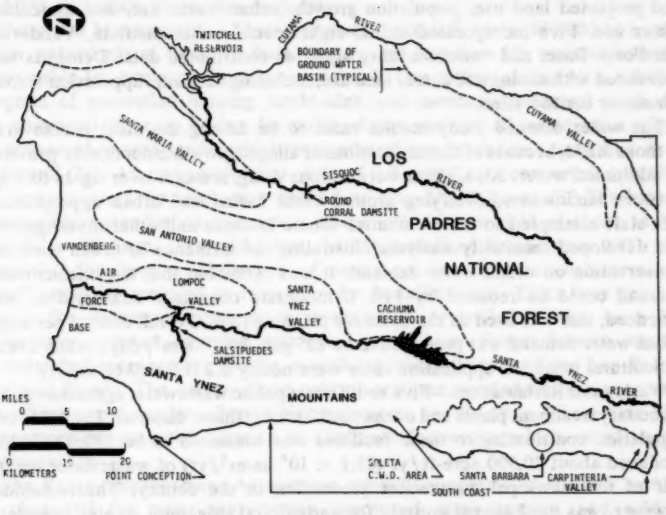

FIG. 2.—Los Padres National Forest

the many alternatives analyzed, the most popular appeared to be local resources management, including conjunctive use of the surface water supplies of the Santa Ynez River with the ground-water basins of the south coast.

County Program of Action.—The Water Agency had been requested by various water entities to take the lead in planning for water resources in the county which would lead to a decision on water importation. The Agency agreed to undertake a so-called "Program of Action for Water Resources Planning," this being an orderly and comprehensive series of investigations and reports that would lead to a decision and implementation of (a) recommended project(s) (5). Although badly split on the issue of state water importation, the Board of Directors adopted the "Program of Action" unanimously and recruited and hired an engineer-manager to direct this work, the overview of which follows.

Comprehensive Studies

The Water Agency staff conducted reconnaissance-level studies of water demands and potential yields and costs of wastewater reclamation, watershed management, weather modification, desalination of saline waters, and groundwater basins. Special assistance was obtained from consultants regarding local dams (2), costs of importing water from existing SWP facilities (4,11), conjunctive use operations (10), and operational aspects of the SWP (3). To help prepare for the water bond election, the Agency used a municipal financing consultant (35), bond counsel (16), and a special consultant for environmental and water resources that consolidated the findings of the previous studies into a single environmental document (13).

Water Demands.—Information was obtained and analyzed on historic, current, and projected land use, population growth, urban water use, and agricultural water use. Five incorporated cities, eight special water districts, Vanderberg Air Force Base, and various county agencies contributed data. Demands were correlated with zoning and actual land use, including demand suppression through consumer conservation.

The water demand study results came to be among the most controversial of those made, because of the implications of alleged growth induction by provision of additional water. Also, there were serious disagreements over rights to water between landowners, overlying ground-water basins and urban appropriators. The staff attempted to steer a neutral course in these and other investigations, and developed sensitivity analyses illustrating the influence of urban consumer conservation on urban water demand. It was estimated that the unconstrained demand could be reduced by 14% if moderate consumer conservation were practiced; this was used as the basis for planning (20). Overall county per capita urban water demand was projected to be 205 gal/day (5.8 m^3/day), while overall agricultural irrigation application rates were nearly 2.2 ft/yr (0.66 m/yr).

Wastewater Reclamation.—Five south coast public wastewater agencies operate secondary treatment plants and ocean outfalls for effluent disposal. The 1975–1976 population contributing to these facilities was estimated to be 170,000, which produced about 20,300 acre-ft/yr (25.1×10^6 ha-m^3/yr) of wastewater, nearly half of the municipal wastewater production in the county. The remainder, however, was used almost entirely for agricultural irrigation, or else percolated to usable aquifers. Thus, the only true potential for creation of new water supply via reuse was on the urban south coast.

Although the water Agency staff did not conduct a market survey of potential user demand for reclaimed wastewater, it did survey water and wastewater entities by a special questionnaire. The results of this effort and of separate studies by private consultants for certain wastewater agencies were used in formulating wastewater reclamation project alternatives for the south coast. These entailed distribution systems serving landscape irrigation and agricultural irrigation in several areas, as well as single, small industrial cooling water reuse. It was assumed that secondary treatment and disinfection would be required for disposal and that such treatment would be sufficient for the reuse projects proposed. Thus, the only capital, operations, and maintenance costs allocable to the reuse projects were for distribution facilities (21).

For planning purposes, the staff assumed no ground-water recharge with

reclaimed water would be implemented in the county until the period 1991–2000, and that dilution with freshwater would be required by health agencies, so that reclaimed water would never represent more than 50% of the total natural recharge. Secondary effluent would have to be given additional treatment by activated carbon adsorption and partial demineralization via reverse osmosis for ground-water recharge by any means, and filtration would be required additionally for injection. These provisions added to the economic and energy costs.

The estimated yields of "new water" from wastewater reclamation/reuse projects were about 9,330 acre-ft/yr (11.5 ha-m^3/yr) on the south coast, and 2,200 acre-ft/yr (2.7 ha-m^3/yr) in the Lompoc area. The majority of the flow was projected to be used for agricultural irrigation but repayment capacity of commercial agriculture was questionable. There were also uncertainties of usability on certain crops, due to quality.

Watershed Management.—There are some 1,600,000 acres (650,000 h) in the major watersheds of Santa Barbara County, but less than 5% were considered manageable for water production purposes. It was estimated that by a suitable program of controlled burning, herbicides, and mechanical control methods, the chapparal in areas having favorable slopes and soil characteristics might be converted to grasslands, which evapotranspirate much less water than does chapparal (28). An estimated water yield of 0.2 acre-ft/yr/converted acre (247 m^3/yr/converted hectare) was applied to the 74,000 acres (30,000 ha) of manageable watershed to calculate a theoretical ultimate yield of about 14,000 acre-ft/yr (17 ha-m^3/yr), with about half that realized by the year 2000, the target date for planning. There was, of course, no assurance that such increased runoff could be captured in reservoirs for beneficial use. There was genuine county fire department interest in programs of controlled burning as a fire suppression measure, coupled with the United States Forest Service interest in watershed management for the overall long-range benefit of the Los Padres National Forest. The county flood control engineer pointed out the potentials for siltation and, under adverse circumstances, for flooding. There was also concern about potential siltation in Cachuma Reservoir, which could impair water quality.

The Range Improvement Association strongly supported controlled burning of chapparal for range rejuvenation, improved cattle grazing, and wildlife enhancement. One of its officers was an outspoken opponent of the SWP proposal, and was joined by two county supervisors and other SWP opponents in advocating watershed management as a major alternative to the SWP, suggesting considerably higher water yields than had been estimated by the Water Agency staff.

Weather Modification.—Santa Barbara County has been the site of extensive, controlled weather modification experiments in the past (15), and experience had demonstrated that increases in rainfall normally resulted from cloud seeding using either ground generators or aircraft. Rainfall augmentation of about 15% appeared to be suitable for planning purposes; however this first had to be converted to increased runoff and, ultimately, to increased yields of reservoirs and ground-water basins. For the reconnaissance-level studies of water supply alternatives, an approximation of rainfall and runoff data for the various watersheds of the county was developed (24).

For each watershed, base flow was approximated from dry weather runoff

conditions, this value then being deducted from wet weather runoff in each of several 30-day periods embracing rainstorms. The incremental runoff over base flow was plotted as a percentage of the measured rainfall for each period.

From such analyses, stylized curves representing early season, midwinter, and spring conditions were drawn. For each data point on the curves, a 15% augmented rainfall was presumed, and a corresponding increase in the runoff at the appropriate point on the proper stylized curve was converted into a runoff quantity. This was done for each stream and usually about three or four storms during each rainy season (November–April) for each of seven recent years of record.

Weather modification appeared quite economical and productive—a long-range yield augmentation of some 25,400 acre-ft/yr (31 ha-m^3/yr) was indicated—but there were concerns over possible flood damage liability, potential adverse environmental impacts, and the uncertainty of cloud seeding with respect to other alternatives (13,19).

Desalination.—Consideration was given to improving the mineral quality (and ostensibly the market value) of reclaimed wastewater for landscape and agricultural irrigation by means of partial desalination. The staff developed potential study projects for these and for pretreatment and partial desalting of certain oil field brines and agricultural irrigation tailwater. Finally, potential seawater desalting projects were studied for various south coast urban areas. Although, theoretically, over 29,000 acre-ft/yr (36 ha-m^3/yr) could be produced by desalination (roughly half from municipal wastewater), the new water thus created would be relatively expensive, energy-intensive to produce, limited in potential applications, and would not be conveniently available where demands might exist (28).

Ground-water Basins Studies.—Various United States Geological Survey studies and certain consultant reports on groundwater in the area were updated for the purpose of incorporating current conditions and practices. Computer modeling was employed where appropriate (24). The total safe yield for extractions was estimated at about 184,000 acre-ft/yr (227 ha-m^3/yr) for the entire county, with a corresponding safe yield for consumptive use of about 135,000 acre-ft/yr (167 ha-m^3/yr). Current overdraft, on an extractions basis, was about 88,500 acre-ft/yr (109 ha-m^3/yr), all of it in the north county, particularly in the Cuyama Valley. Calculations showed virtually all of the basins to have an adverse salt balance and a theoretical buildup of salts. Overdrafts were indicated in both the Lompoc and Santa Maria basins, but no seawater intrusion was being experienced because of apparently adequate subsurface outflow.

Local Dam Development Potentials.—The Santa Ynez River is regulated by three reservoirs and the Santa Maria River by one (on the Cuyama tributary). Consideration was given to the following possibilities: (1) Enlarging the largest Santa Ynez River reservoir (Cachuma); (2) constructing an impounding dam on a major downstream tributary to this river (Salsipuedes Creek); (3) developing spreading grounds on the Santa Ynez and Santa Maria Rivers; (4) constructing an impounding dam on the Sisquoc River; and (5) constructing dams on various south coast streams. The Cachuma Reservoir safe yield is about 24,800 acre-ft/yr (30.6 ha-m^3/yr), and is augmented by about 3,000 acre-ft/yr (3.7 ha-m^3/yr) of Tecolote Tunnel infiltration. The reservoir yield had been variously estimated to be capable of augmentation by 27% with a 50% capacity increase, to as

much as an 80% increase by trebling the existing capacity of 205,000 acre-ft/yr (252 ha-m^3/yr), (2,36), but the Bureau of Reclamation would not assure that any significant dam enlargement could be undertaken until a comprehensive feasibility study had so demonstrated. Upstream reservoirs were not attractive for enlargement, due to geologic considerations, limited watersheds, or severe siltation potentials, or all these factors. The downstream tributary development on Salsipuedes Creek was costly, but a 50,000-acre-ft (61.7-ha-m^3) capacity reservoir would produce 6,530 acre-ft/yr (8.05 ha-m^3/yr) when operated for ground-water recharge. On the other hand, a Round Corral Reservoir on the Sisquoc River, with 82,000-acre-ft (101-ha-m^3) capacity would be very costly, and would only produce 6,700 acre-ft/yr (8.3 ha-m^3/yr) when operated for downstream ground-water basin replenishment (2).

Studies of south coast dam development potentials showed limited yields, high costs, and serious risks of siltation due to the steep, limited watersheds, flashy runoff, and erosion potentials (23).

State Water Importation Costs.—Staff and consultant work on SWP water inportation proceeded concurrently with the studies of local alternatives. The complexities, magnitude, and contractual implications of importation required considerably more study than did many if local alternatives. A consultant prepared a report on a Ventura County route for SWP importation for the south coast (11), while the staff conducted a series of cost studies on coastal aqueduct importation and intracounty distribution (18,27), including projected inflation. Water pricing policies were adopted, which reflected actual costs to the point of delivery and commitments for future water deliveries obtained from local water purveyors.

The staff's initial report on costs of state water (18) had indicated preliminary unit costs ranging from $227/acre-ft ($0.184/m^3) in the Santa Maria Valley to as much as $570 acre-ft ($0.462/m^3) for the Lompoc area, the former based on a maximum entitlement importation, and the latter on a reduced level of importation. The cited unit costs were based on late 1977 price levels, full capacity utilization, and general obligation bond financing. Pumping energy costs were already assumed to be very significant. The effects of escalating costs, energy requirements, DWR difficulties in meeting contractual obligations, and the open-ended nature of the water supply contract, were emphasized by the staff report.

Conjunctive Use of Groundwater and Surface Water.—Next to the state water importation itself, this alternative was the most controversial. It had widespread appeal among environmentally-oriented persons and limited growth advocates, because of its ostensible emphasis on resource management rather than on development of new facilities. It had considerably less support from most water engineers and attorneys, as well as water interests, in the area of surface water origin, the Santa Ynez River watershed. The general proposal was for changing the operation of Cachuma Reservoir from safe yield mode to conjunctive mode (with south coast and certain Santa Ynez basin ground-water basins) permitting reservoir drawdown for maximum diversions during wet years. This would salvage certain surface water otherwise lost by evaporation or unrecovered reservoir spill. During dry years, the bulk of the supply would come from the ground-water basins, which by then would have considerable water in storage. Inasmuch as no engineering study yet performed had answered all relevant hydrologic,

engineering, legal, economic, jurisdictional, and feasibility questions, both advocates and skeptics alike agreed that a comprehensive study should be undertaken.

A two-phased consultant study was authorized, based on using data developed by the consultant and other water entities and an existing computer model. The consultant's first-phase report (10) indicated a yield of 10,000 acre-ft/yr–20,000 acre-ft/yr (12.3 ha-m^3/yr–23.7 ha-m^3/yr) could be expected from conjunctive use operations of the Santa Ynez River reservoirs with the south coast and Lompoc ground-water basins. However, the Lompoc basin would sustain extreme water table fluctuations, and many doubted the feasibility of this arrangement.

To provide an independent check on the potentials for conjunctive use yield, the Agency staff analyzed the maximum potential of the river system to provide surplus for conjunctive operation with the local Santa Ynez Upland ground-water basin and the south coast basins. A yield of about 10,000 acre-ft/yr (12.3 ha-m^3/yr) appeared to be a reasonable upper limit (25), but a range of unit costs estimated by the staff indicated that conjunctive use would be more costly than previously supposed, due to the need for substantial facilities for in-lieu surface deliveries, or artificial recharge and recovery, or both. Moreover, the estimated yield premise was based upon a usable ground-water storage capacity of 200,000 acre-ft (247 ha-m^3), and the yield included a 3,000-acre-ft/yr (3.7-ha-m^3/yr) component that supposedly could be realized simply by modifying downstream releases from the Cachuma Reservoir. Clearly, the availability of usable ground-water basin storage for conjunctive operation was an important yield constraint, an approximate ratio of storage to annual yield being on the order of 20:1. There was disagreement amoung various engineer representatives as to the proper value of usable storage for planning purposes, some being more conservative than others but all agreeing that definitive data should be systematically collected to this end. A special committee studied conjunctive use (33), but the recommendation was not unaminous.

Water Rights.—Rights to local water supply were in dispute in a number of instances. To aid the appraisals of supply adequacy among various water entities, the staff identified various water rights, claims, and disagreements in a reconnaissance-level report (26). The validity of water rights obviously affects the needs for supplemental supply on the parts of public agencies, water companies, and private parties.

In one important case, the south coast agencies and the Bureau of Reclamation opposed the water districts representing the Santa Ynez Valley before the State Water Resources Control Board (SWRCB) regarding the latter's claim of watershed-of-origin rights to the Santa Ynez River, including rights to appropriate from riparian wells. The south coast and the Bureau protested that such development would indirectly work a hardship on the south coast by reducing the yield of the Cachuma Project and depriving the south coast of flow, so that prior rights might be satisfied. The SWRCB found for the Santa Ynez Valley districts, thereby reducing the latter's reliance on imported supply, although the Cachuma yield was not actually curtailed (9).

In another key case, the Goleta County Water District (GCWD), which had been sued by certain landowners within its territory who had been denied water service filed a cross complaint and additionally named many private and public landowners and well operators within the Goleta Ground Water Basin as

defendants (39). The GCWD claimed rights to a major portion of the basin's yield under the doctrine of public interest, noting the great expense it had undertaken to supply GCWD inhabitants with water and the reliance they placed upon such supply. The GCWD was actually deficient in supply, but had a public initiative-reinforced policy of favoring local supply developments over new imported supply. The directors of the GCWD and other growth control advocates had unsuccessfully urged the County Board of Supervisors to rescind a policy of permitting the drilling of private wells for nonagricultural purposes within any water district where there was a declared water moratorium, contending that such new wells would reduce the supply available to those already using the basin. It was claimed that the Board's first duty was to maintain supply for those inhabitants it had already permitted by zoning and building permits, to develop and occupy land, and not to diminish such supply by allowing others to intrude. However, county counsel advised that until such time as a ground-water overdraft existed and a foreseeable threat to the public health became apparent, such a prohibition could constitute an inverse taking by the county of water rights and essentially, of the private property for which it would be liable (38).

The Superior Court eventually agreed with the GCWD assertion of a moderate basin safe yield, and not a higher value contended by certain land developers. The Court also agreed that the district's pumping as an appropriator had established public use priority in favor of the district. However, the Court reduced the GCWD entitlement to basin yield from the level sought by the GCWD, from considerations of correlative rights of overlying owners.

Overlying rights to groundwater had always been a fundamental of California water law, but this was now being questioned by Goleta's public interest doctrine and by the Governor's Commission to Investigate California Water Rights. Understandably, farmers and would-be land developers opposed any alteration of the traditional water right, while environmentalists and limited growth advocates generally favored ground-water basin management under government control (7,30).

SWP Operations and Costs.—It was established that the SWP existing conservation facilities had a capability of producing about 2,300,000 acre-ft/yr (2,840 ha-m^3/yr) based on 7-yr critical dry period (equivalent to 1928–1934 historical data) (6,12).

The SWP had contracted for 4,300,000 acre-ft/yr depending on the development of added water conservation projects to meet the buildup of demand. A special consultant report to the Water Agency (3) considered the reliability of the SWP, and the ways in which it might be made to coordinate with local sources. The report noted that simultaneous droughts in both northern and southern California were infrequent, and that imported supply should provide considerable insurance against shortages. The county's SWP contract was essentially for municipal supply and therefore not subject to agricultural curtailments, as provided in the contract during shortages. Retention of its full entitlement by the county could partially protect its lesser subscription deliveries from dry year curtailments, at a price. Cachuma's yield could actually be augmented by some 1,400 acre-ft/yr (1.7 ha-m^3/yr) if operated conjunctively with the SWP.

The SWP water would be very much lower in mineral content than local supplies (about one third lower on the average), and the county's water purveyors

had taken this quality factor into account in submitting initial subscriptions for SWP water. The requests from purveyors indicated an initial desire for about 33% of the county's maximum entitlement, and an ultimate desire for about 59% of maximum entitlement, which was somewhat lower than the original concept. However, the full pipeline capacity for future deliveries would have to be constructed at the outset, and payments revenues required from limited water sales during the buildup years, produced comparatively high unit costs.

Interest quickened in the possibilities of the county's selling at least a portion of its entitlements to aqueduct capacity and future water deliveries in the SWP. Opponents of importation desired all of the county's existing adueduct capacity to be disposed of, but many desired the DWR to undertake local projects to produce water under the contract in lieu of imported water, as proposed by the DWR. Certain San Joaquin Valley water districts evinced interest in the county's entitlements, but the DWR, would not permit transfer of entitlements among its water supply contractors, except on its own restrictive terms. Meanwhile, rising annual payments to the state from property taxes were becoming burdensome.

A bond proposal was offered by the flood control and water conservation district, as a countywide ballot measure for $120,000,000 in revenue bonds, for the construction and financing of the in-county facilities. Connecting state facilities did not require a vote.

General obligation bond financing of in-county facilities was denied by the statewide Proposition 13 initiative, leaving revenue bonds at higher interest rates without significant ad valorum tax assistance to support the project. The ballot measure to finance the in-county facilities was set at $102,000,000, including reserves and other costs. The 7-yr period for construction of both state and county facilities made forecasting inflation of costs a major problem. The state is obligated by the 1963 contract to finance and construct the aqueduct from the San Joaquin Valley to Santa Maria and could do so using presently authorized bonds. They would not do so unless the county was prepared to construct its in-county facilities.

Information Summary.—The Environmental and Water Resources Reconnaissance report was published two months before the March 1979, election, and presented at public hearings (15). This document provided a digest for the preceding study reports, a reconnaissance assessment of environmental impacts resulting from the proposed importation and various supply alternatives, and an analysis of growth inducement by added water supplies. A sensitivity analysis of alternative growth rates (and future water demands) and their impacts on new water supply development was included. Table 1 presents an excerpt from this analysis. Fig. 3 indicates the relative magnitude of the purveyors' SWP subscriptions, the available water supplies, and alternatively projected demands and deficits. Fig. 4 presents a simplified illustration of yields and costs (early 1978 price levels) of alternative supply projects.

As indicated in Table 1 and Fig. 3, importation from the SWP could do much to alleviate present and future water deficits in many county areas but would still leave room for local resources development. Due to substantial costs, it was unlikely that a municipality would participate in, or undertake individually, more than one project, and then only to the degree necessary to reduce its own deficits, or improve its water quality, or both. There would be no direct

assistance by a municipality of its rural neighbors in its taking state water, but indirectly it could benefit rural water producers by furnishing more municipal needs from imported high quality water, leaving ground-water supplies for rural and agricultural use. Thus, it was likely that deficits would still exist even with importation. Agricultural-type districts and unorganized rural areas were unwilling or unable to participate in project developments, even in some of the less expensive alternatives.

Election Campaign

Having set the date for the election, the County Board of Supervisors was unable to take a position on the proposal. Two members were staunch supporters

TABLE 1.—Projected Water Demands, Deficits, and SWP Subscriptions, in 1,000 acre-ft/yr

Location in Santa Barbara County (1)	Present Condition			Year 2000	Condition A[b]		Condition B[c]		SWP Purveyor[d]
	Supply (2)	Demand (3)	Deficit (4)	supply[a] (5)	Demand (6)	Deficit (7)	Demand (8)	Deficit (9)	Subscriptions (10)
South coast urban area	48.06	46.73	(1.33)	45.00	51.11	6.11	58.33	13.33	13.70
Santa Ynez Valley	24.68	25.47	0.79	23.77	26.21	2.44	23.66	(0.11)	2.68
Lompoc and San Antonio Valley	28.55	35.82	7.27	29.40	37.05	7.65	42.92	13.52	9.35
Santa Maria Valley	65.80	81.93	16.13	67.50	84.73	17.23	91.60	24.10	11.25
Total, excluding Cuyama Valley and westerly south coast	167.09	189.95	22.86	165.67	199.10	33.43	216.51	50.84	36.98

[a]Differences in supply values from the present to the year 2000 are due to reservoir siltation, contractual reallocations of Cachuma entitlements, and increases in coastal ground-water basin yield due, to reduced outflows and consumptive use losses.

[b]Condition A allowed for no growth at all in irrigated agricultural demands. Population growth was 1% annually, this being generally consonant with tentatively accepted county planning values.

[c]Condition B is the same as Condition A, except that agricultural growth is provided for as projected by the Water Agency staff.

[d]Level of SWP subscriptions by the year 2000 for the 13 subscribing purveyors, plus an allowance for the GCWD.

Note: 1,000 acre-ft/yr = 1.2335 ha-m^3.

of SWP importation, and two others, who became supervisors in January 1977, were adamantly and vigorously opposed to it, and even led the opposition committee. They signed the ballot arguments, pro and con, respectively. The fifth member sponsored a special panel group to examine the complex issues, subsequently taking a position of neutrality. His chief reservations about the SWP proposal were in its growth-inducing potentials. Even a 3 to 2 position of the Board of Supervisors was unobtainable. On a split vote, the Board approved countywide dissemination of an information sheet via newspaper inserts for

the voters prior to the election. Opponents of water importation published their own information sheet in a local newspaper generally sympathetic to this view.

The election campaign became quite emotional, because the stakes were considered high. Many panel examinations and speeches were held before various community groups throughout the county. Project opponents representing growth limitation were well organized and attacked the SWP proposal from many angles, questioning staff reports and figures and claiming oversubscription by the purveyors. They stressed the high cost of the supplemental SWP water, and alleged its unreliability, its growth-inducing potentials, and the absence of a true need for it when water demands were curtailed, and less environmentally-disruptive local alternatives were pursued. These arguments contained some elements of truth and well-prepared pro advocates were not in evidence. The

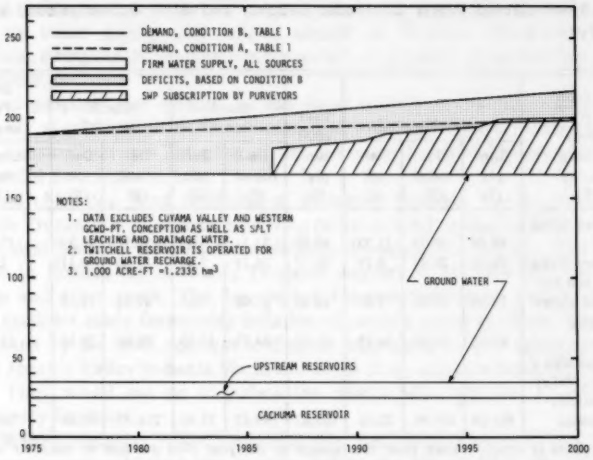

FIG. 3.—Relative magnitude of Purveyors' SWP Subscriptions, Available Water Supplies, and Alternatively Projected Demands and Deficits

SWP program was also alleged to be more capital-intensive and many local alternatives appeared relatively attractive in theory. The arguments questioning their practicability were generally discounted by importation opponents. Staff engineers were constrained by the split opinions of the Board of Supervisors against taking any advocate position.

Arguments arose against the importation on the basis of facilitating urbanization of agricultural lands by driving land values up so high that urban pressures would become irresistible. A counter argument was used that without adequate water, agriculture would be forced out by priority demands for municipal water for urban development, which normally used less water consumptively than agriculture. Land use control by control of water shortage was felt by many to be more positive than land use control by general plan and zoning administration, which could be changed or relaxed by actions of elected bodies.

The county had been delayed in adopting a new comprehensive plan which should have facilitated demand projections, and this was taken to be an additional reason by project opponents to reject the bond proposal. They argued that water supply should not be made available beyond the quantities yet to be determined by the new plan when adopted. Normal considerations for prudent planning for supply reserves and system flexibility were attacked as being growth-inducing and costly.

The newspapers' letters to the editors reflected the multifaceted controversy as the campaign went on. Citizens' organizations took positions on the proposal, and most were in opposition. They were joined conspicuously by two state legislators representing the area. The GCWD Board of Directors presented its

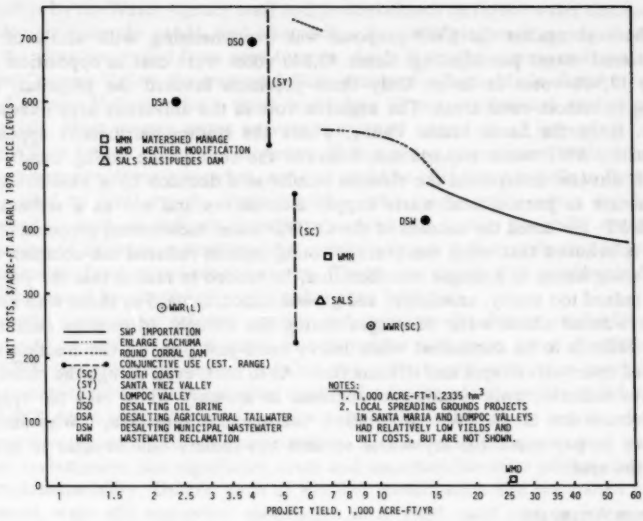

FIG. 4.—Simplified Illustration of Yields and Costs of Alternative Supply Projects

own advisory ballot proposal for a reclaimed wastewater irrigation project and disparaged the SWP proposal in its ballot information. The local branch of the University of California is centered within the district, and the students and academic community for the most part were enthusiastically opposed to the SWP measure for growth reasons. Only a relatively few conservative and traditional organizations, such as certain chambers of commerce, rural water districts, and the County Farm Bureau, came out in support of the SWP proposal. Individual water purveyors and cities favored the proposal, but were cautious due to their own Proposition 13 tax constraints.

Two outspoken SWP opponents from the southern Delta appeared before the Board of Supervisors two weeks before the election, at the request of one of the opposition supervisors. They denounced the state's peripheral canal

proposal and the county's proposal to import SWP water, favoring an increase in SWP conservation storage, and a limitation on delta export. One week later, a DWR deputy director appeared before the Board at the request of another supervisor, clarified certain information and indirectly offered a mild rebuttal to the presentation of the previous week (12). The DWR itself remained neutral to the county's proposal. However, most county newspapers formally favored the proposal. In contrast, a prominent San Francisco newspaper editorialized against it. Certain San Joaquin County farm interests contributed substantial funds to the organization opposing the importation, with hopes of requiring the county's water entitlement.

Election

The vote against the SWP proposal was overwhelming, with 42.3% of the registered voters participating. Some 43,846 votes were cast in opposition and only 17,301 votes in favor. Only three precincts favored the proposal, two being in remote rural areas. The negative vote in the university area exceeded 90%. Even the Santa Maria Valley, where the studies particularly appeared to justify SWP water importation, followed the countywide voting trend. The DWR director interpreted the election results as a decision by a well-informed electorate to pursue local water supply alternatives and not as a setback to the SWP. He noted the success of the GCWD water reclamation proposal (17).

It is believed that when the average voting layman reduced the complex and confusing issues to a simple consideration, he tended to reason that the project was indeed too costly, unreliable, and growth-encouraging. For those who might have worried about water shortages during the drought 14 months earlier, it was difficult to be concerned when heavy rains just prior to the election had caused reservoirs to spill and streams flow. As to cost, even though the county's figures indicated only a moderate increase in monthly water bills for typical consumers due to the SWP importation, the question remained, "Why should I have to pay more for my water so that newcomers will be able to move into the area?"

Election Aftermath

The urgency for development of local resources seemed to recede as public officials and the electorate alike became preoccupied with other matters. Although the DWR had developed guidelines for consideration of local projects for integration into the SWP 1 yr before the election, some 18 months after the election, the Board of Supervisors had not yet submitted any request to the DWR for a local project, not even a relatively straightforward off-channel spreading grounds project. Indeed there was some sentiment limiting any further county sponsorship of water projects.

The state peripheral canal bill passed in 1980, which authorized the added water conservation projects to meet contractual demands. It was signed into law and promptly attacked by referendum action. The DWR had tentatively approved temporary transfer of the county's water entitlement to willing San Joaquin Valley purchasers contingent on the peripheral canal law, but this is held up, pending the referendum vote. Thus, the county's annual cost under

the SWP contract continues. Public sentiment seems to favor retaining the rights in state water for the future, even though limited growth advocates claim the 1979 vote was a mandate to end the SWP contract at any cost. The county comprehensive plan should be adopted by the end of 1980.

The GCWD water reclamation/reuse project was moving slowly, not yet under engineering design, and lacking formal commitments from potential reclaimed water users. Federal water pollution control funds were no longer being extended to financing reclamation projects. However, certain state funds were authorized and might assist here and elsewhere.

Summary and Conclusions

Studies by the Water Agency staff and its consultants on future water demands, supplemental supply needs, and alternatives for satisfying such needs showed that the situation varied from area to area. Aside from the remote and sparsely settled Cuyama Valley, the greatest deficits occurred in Santa Maria, San Antonio, and Lompoc Valleys where there were few if any wastewater reclamation potentials. Most county water purveyors evinced intentions of importing from the SWP on behalf of urban customers. Urban water importation could relieve ground-water pumping somewhat, and this could be of indirect benefit to farmers who relied on local supply. Project critics, who were mostly urban dwellers, objected to such an indirect benefit to agriculture. Critics generally opposed expansion of irrigated agriculture, the county's largest industry, fearing ultimate urbanization from economic pressures. There was an implicit preference for growth control by control of water rather than land use.

Despite its superior mineral quality and certainty for future availability to all county areas (except Cuyama), in comparison with most local alternatives, the SWP was relatively costly, entailed unusually heavy early year payments, and required considerable pumping energy. Its future adequacy depended upon the DWR developing additional conservation facilities in a timely manner. Local alternatives appealing to environmentalists, such as conjunctive use and wastewater reclamation, had significant costs and uncertainties as to market demand or implementability. Others, such as weather modification and watershed management, were still somewhat speculative as to yield, cost, and environmental impact. Very few dams appeared feasible, and these were costly and limited in areas of benefit. There appeared to be room and need for both the SWP and local alternatives, but the need and justification would be greatly reduced if future demands were contained. Costs for maintaining the county's importation option continued and will increase until entitlements are transferred temporarily, or the contract terminated.

The voters considered these complex matters during an emotional election campaign, and then soundly defeated the SWP bond proposal, even in Santa Maria Valley, where supplemental water prospects from other sources were unusually limited. It is concluded that the majority of the voters felt the county was nearing maturity concerning its growth, and were unwilling to underwrite an increased water supply for the future.

The Board of Supervisors, in 1963, contracted for SWP water, based on sound engineering advice that it would be needed about 1980. The 1975 Board directed the engineering planning, including the study of alternatives and environ-

mental review, which would lead to a decision on the SWP importation project. Changes in public opinion, as evidenced by population limitation actions and growth limitation advocates, and a significant change in the position of the Board of Supervisors in 1977, prevented the engineering planning from leading to a logical decision based on technical and factual findings. The hoped-for resolution of the problem by the March 1979 vote, is really no resolution at all, and it is unfortunate that the residents of Santa Barbara County will have to face the water problem in the future at greater cost.

Acknowledgments

The substantial contributions of the entire Water Agency staff are gratefully acknowledged, as are the cooperation and assistance of other county colleagues and water purveyor representatives. Special recognition is given to Jon A. Ahlroth. The writer appreciates the editing of their paper by Norman H. Caldwell, F. ASCE.

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RISK AVOIDANCE OBJECTIVE IN WATER RESOURCES

By Ata M. Nazar,[1] Warren A. Hall,[2] and Maurice L. Albertson[3]

INTRODUCTION

Among the most important considerations in water resources planning and management are the provisions of assurances that: (1) Certain quantities of water be available when and where needed; (2) certain quantities of water, with the same quality characteristics as the "needed" water, not be present when and where they are not needed; and (3) stated quantities of hydroelectric energy be available when and where needed. The same conditions of assurance dominate most other water resources objectives.

The value of water and energy is not determined, as commonly assumed by most lay individuals and by no inconsiderable number of experts, simply by multiplying a unit price by the number of units involved. Rather, it is determined primarily by the degree of assurance with which that quantity of water will be available over substantial periods of time, when and where it is needed. For example, lightening represents significant quantities of electricity. However, it is considered worthless (actually destructive) because its availability in time and place in exceedingly unreliable.

Most water resource development systems actually reduce the quantities of water available, and none create new quantities. If unit price were representative of the value of water without consideration of its assurance in time and place, over time, then no reservoirs or other water system elements would be needed.

The purpose of this paper is to present a methodology for the quantitative evaluation of the level of assurance or reliability associated with various levels

[1]Grad. Research Assoc., Dept. of Civ. Engrg., Colorado State Univ., Fort Collins, Colo. 80521; on leave, Instr. in Civ. Engrg., Kabul Univ., Afghanistan.
[2]Prof., Dept. of Civ. Engrg., Colorado State Univ., Fort Collins, Colo. 80523.
[3]Prof., Dept. of Civ. Engrg., Colorado State Univ., Fort Collins, Colo. 80523.

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of project output, and to determine the trade-off between reliability and a nominal level of service from the project, so that appropriate decisions concerning these two factors can be made more objectively than at present.

Assurance

As important as the requirement of assurance has always been and will continue to be for water resources, it has seldom been incorporated explicitly as an objective in the planning and operational processes. Rather, it has been implicitly incorporated by the use of a number of concepts ranging from "firm energy" and "firm water" to water rights doctrines, which then in turn are used as constraints (5). In only a few cases is the resultant reliability even estimated. For example, the most commonly-used definition of firm water (or firm energy) is that level of service which can be provided according to an anticipated demand schedule over time (and place) by the water resource system without fail, if the historical sequence of hydrologic events were to repeat itself exactly.

This is not an assumption that history will repeat itself in the future, despite criticisms alleging this is so. Rather, it is simply a convenient, reproducible definition of firm water or firm energy for use in assessing the capabilities of a project to perform satisfactorily. Nor does it assume that the quantities so defined will in fact be available 100% of the time in the future.

Rather, it is a recognition of the fact that satisfactory explicit measures of the assurance have not been available; thus an implicit constraint must be introduced to assure that this fundamental objective is met in a reasonably satisfactory manner. The assumption is implicitly made that, if the "firm" level is defined and estimated in this manner, using all of the historical hydrological data available for the streamflow, then the implicit level of assurance is either satisfactory or the best that can be provided with the data available.

Risk

When viewed from the perspective of an objective in a multiple-objective analysis, the complexity of the risk problem quickly becomes apparent. Risk of what? It is not sufficient to reply risk of a failure to deliver the firm levels of project output. Failure itself is multifaceted. One might fail to deliver in an overtime period the planned firm output of water by a few cubic centimeters (which would be completely trivial), or one might fail to deliver the output by any other amount up to and including the full anticipated output (which would be very, very unlikely). This produces an infinite number of quantitative outcomes, for each of which minimization of the probability of occurrence could be an objective. Furthermore, it is apparent that the actual worth of minimizing each probability is not at all uniform over this spectrum.

As if this were not enough complexity, the manner in which the degree of deficiency is distributed over its duration may be as important or more important than the gross magnitude itself.

The definitions of "firm" outputs customarily used are thus seen to be very useful expedients, since all of the aforementioned concepts are implicitly considered even though they have not been explicitly evaluated. However, as analytical capabilities improve, particularly those associated with mathematical

optimization, these implicit constraints representing implicit objectives have come into question. Should projects be designed to meet the rigid definition or does the true optimum involve a trade-off between cost, reliability, and nominal level of output? After all, the levels of reliability associated with a firm output based on 10 yr of historical record is hardly the same as that based on 50 yr or 100 yr of record, yet each would be considerd to be the correct value if they were all the records available.

In order to assess the trade-off between the marginal gains and losses in reliability and other objectives such as cost, water, energy, etc., it is essential to define explicit measures of reliability or risk which can be evaluated for any proposed design or set operational rules. Since in theory at least, this implies that a virtually infinite number of such indices would be necessary, the few specific indices selected and defined must, in effect, be rational representatives of the entire spectrum.

Approach

The approach adopted in this analysis is to simulate the operation of the system by using a long synthetic record of inflow, generated from the relatively short historical record of the stream feeding the reservoir, but retaining the same statistical characteristics. The system operation is to be tested with this synthetic record, and the release policies determined that are necessary to meet the stated design irrigation and energy requirements in full. Any consecutive period of time for which these requirements cannot be met is defined as a failure event. All such system failures, including the total amount of the deficiency and the duration of failure condition, are to be determined for several different design requirements. The resulting information allows the definition of risk parameters and the evaluation of the associated risk probabilities for that range of system operation. The parameters so obtained could then be included in a multiple-objective function for the system to be optimized.

Although there are a large number of such risks of combinations of specific magnitudes and specific durations, these are not necessarily independent. In general, it might be possible that for actions which minimize the probability of one particular magnitude and duration being exceeded, the exceedance probability of a fairly large range of other magnitudes and durations would also be greatly decreased if not actually minimized. Thus, it might be expected that a relatively small number of combinations of magnitude and duration could be used as the representatives of all other important risk objectives, thereby greatly simplifying the problem.

Problem

The basic problem consists of two parts:

1. What specific magnitudes and durations might be used as the representatives of the risk issue?
2. How can the risk itself be determined for these representative magnitudes?

The analysis presented here is directed primarily at the second question. The

methodology presented is capable of determining the risk in terms of exceedance probability for all magnitudes of total deficit, maximum deficit, or durations of failure events, or both.

The approach utilizes a Monte Carlo simulation of a very long sequence of hydrologic events, any n-year subset which can be considered equally likely to occur. This sequence is then used with the design operating policy under a prestated release rule. The rule used in the example is to produce the target water and energy requirements if feasible, but if not feasible (failure), then the release is whatever is available. However, any other desired release rule can be utilized. Indeed, the evaluation of such release rules is an important use of the method.

When the streamflow record is available but considered to be of short duration, a number of mathematical models have been developed, such as those of Beard, Fiering, Mandelbrot and Wallis (3). These can generate, from the available record, additional "equally likely" sequences for any length of time desired. The generated and historical data are presumed to be statistically the same—i.e., their skew, mean, standard deviation, and serial correlation between consecutive months are the same for all practical reservoir analysis purposes.

The 20-yr streamflow record available for the Kunduz River, used as the example in this study, is of insufficient length to evaluate questions of risk. By using the Fiering Model (3), a 900-yr sequence of equally likely streamflow events were generated from the available record. The generated data are then used as an input to the reservoir mass balance equation used as a recursive model for the simulation of the operation of the Qalagai Dam and Reservoir Project in Afghanistan over this 900-yr period.

Mass Balance Analysis

A computer program was used to generate the streamflow data as an input to the reservoir and perform the reservoir inflow-outflow mass balance analysis over time. The analysis begins with some specified quantity of water in storage, usually, but not necessarily, full. Based on monthly inflow, evaporation, and release from the system to meet the targeted regional irrigation and energy requirements, the storage level at each subsequent month is computed. Beginning with full storage, the volume of water that will be available in storage at the end of the first month of system operation is:

$$B_i = Q_i + Y_i - K_i A(Q_i) - R_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which B_i = the volume balance index; Q_i = the volume of water in the reservoir at the beginning of month i; Y_i = the anticipated inflow to the system during month i; K_i = the evaporation rate per unit area of the water surface, A, in the reservoir in month i; and R_i = the volume of release form the reservoir for irrigation and hydropower generation.

The volume balance index, B_i, represents the volume of water in storage at the beginning of the next month, if B_i is equal to or less than the maximum capacity. Thus, Q_{i+1} is set equal to B_i if $B_i \leq S_{max}$ (maximum available storage), and $B_i \geq S_{min}$. If $B_i < S_{min}$, then the system fails to meet water and energy requirements at firm level. These events are noted, and the actual release is computed as whatever water is available. The failure event will continue until

$B_i > S_{min}$ once again. On the other hand, if $B_i > S_{max}$, then the excess water will be considered to bypass the turbine system and the water in storage at the beginning of the next month will be equal to the maximum storage or $Q_{i+1} = S_{max}$.

The water release from the reservoir must meet both irrigation and energy requirements. The two requirements are presumed known and fixed quantities for each month of the year, but they are not necessarily equal. Although water for irrigation and energy are fixed quantities for each month of the year, the volume of water required to generate a fixed amount of energy, will vary according to the water level in the reservoir and is determined by using the following equation:

$$R_{Ei} = \frac{E_i}{(9.806 \times H \times \text{Eff})} 3{,}600 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which R_{Ei} = the volume of release in millions of cubic meters per month required to generate Ei; Ei = the monthly energy requirement in millions of kilowatt hours; H = the gross head in meters; and Eff = the system efficiency.

In order for both irrigation and energy requirements to be satisfied, the computer program is written such that the volume of both requirements are compared and the larger of the two is released. Thus, the other or the smaller need is automatically met because water released for one purpose is also available for the other, or water released for irrigation has to pass through turbines, and water released for power is available for irrigation.

System Characteristic Equations

In Eqs. 1 and 2, there are additional variables which are also affected by the available volume of water in the reservoir. These variables may be usually expressed as power functions of the available water in the reservoir:

$$A = C_7(Q_i)^{C_8} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$H = C_1(Q_i)^{C_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$\text{Eff} = 0.7 + 0.0002(Q_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

in which Q_i is as previously defined; A = the surface area of the available storage in the reservoir which affects evaporation; H is also as previously defined, and affects the volume of water required to generate the monthly firm energy; and Eff which is defined earlier, varies approximately from 72.5%–90.5%.

The constants in Eqs. 3–5 are not fixed values; they are characteristic of each reservoir site and therefore have to be individually determined. For the Qalagai Dam and Reservoir, the constants used in Eqs. 3 and 4 are determined, and their numerical values are: $C_1 = 1.21700$; $C_2 = 0.55800$; $C_7 = 1.47257$; and $C_8 = 0.44200$. If this representation is not sufficiently accurate, the information can be provided as data pairs for various equal increments of Q.

Analysis of Computer Output

The computer recognizes the system inability to fully meet the firm water and energy requirements by checking the volume balance index, B_i, at the

beginning of each month. The system fails to meet its firm level commitment when $B_i < S_{min}$, and the failure event is defined as continuing until B_i again becomes equal to or greater than the minimum storage level. This definition of failure does not depend upon the magnitude of the failure. For example, if the target release is 250,000,000 m^3 of water, then the computer will declare system failure if 249,900,000 m^3 were released. However, the failure event is considered to continue until the target release is feasible once again.

The system may fail to meet the requirements in one period or for any number of consecutive periods of time before it reaches the stage where it can fully

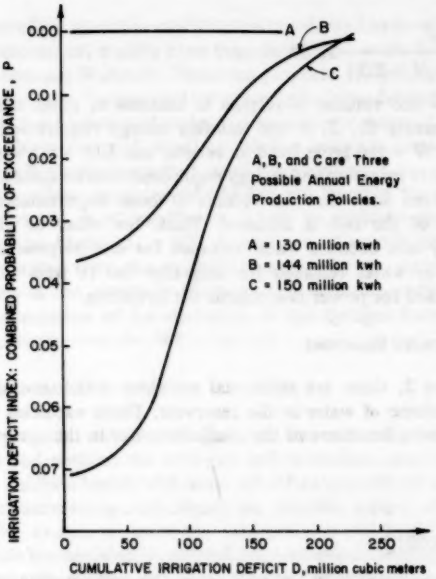

FIG. 1.—Three Possible Annual Energy Production Policies for Qalagai Reservoir in Kunduz River Valley, Afghanistan

satisfy the requirements. During this interval, the magnitudes of the difference between the target release and the actual feasible release are determined as a function of the time periods in which they occur.

The cumulative deficit, D, time duration, T, and the single largest deficit, d, for each complete failure (failure starts when $B_i < S_{min}$ and ends when $B_i \geq S_{min}$) are determined from the failure magnitudes and the consecutive interval of nonzero deficit magnitudes. The D, T, and d values for each failure event in the entire simulation process can thus be determined.

For each of the three parameters, namely D, T, and d, the exceedance probability for any given level can then be calculated, given that a failure (as defined)

occurs. This is the conditional probability which can then be modified by the failure probability itself.

In the example used for this analysis, because of high correlation among the parameters, it was found that only the cumulative deficit, D, is sufficient for this particular project.

In the example problem, two production policies were analyzed. Each of the two operation policies resulted in enough failure events that a fairly accurate plot of integrated exceedance probability for each policy became possible.

Results of Analysis

Computations were made for the Qalagai Dam and reservoir project in Afghanistan on the basis of three "firm energy" levels, 130,000,000 kwh/yr,

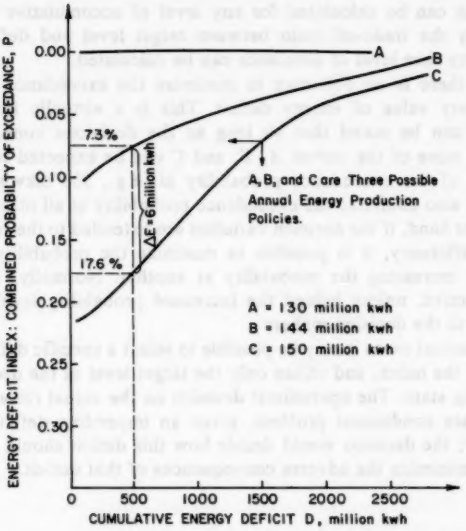

FIG. 2.—Effect of Three Possible Annual Energy Production Policies on Irrigation Deficits for Qalagai Reservoir

144,000,000 kwh/yr, and 150,000,000 kwh/yr. The system had no failure at 130,000,000 kwh/yr energy production policy. For this particular project, the energy requirements dominated over water requirements. That is, each failure to meet firm water requirements in full occurred within a period of failure to meet firm energy requirements.

The results of these calculations are shown in Figs. 1 and 2. In Fig. 1, the abscissa is the level of cumulative energy deficit, and the ordinate is the probability that a deficit equalling or exceeding that level will occur (be initiated) in any given year.

Note that the higher demand levels do not appreciably affect the risk of extremely large deficiencies but do significantly decrease the level of assurance at lower magnitudes of accumulative deficits.

Other indices of deficit could have been used as well, e.g., the mean deficit (cumulative divided by duration) or the maximum single period deficit. The accumulative deficit might also be expressed in terms of the percentage of the annual energy target, or such other terms as desired.

The data also illustrate the approximate trade-off between nominal target output level and assurance. A marginal increase in target output of 6,000,000 kwh/yr at the 144,000,000 kwh level increases the risk of a 500,000,000 kwh deficit by nearly 10%, whereas a change of 14,000,000 kwh at the 130,000,000 kwh level increases the risk by about 7.3%. Thus, the trade-off ratio at 130,000,000 is 0.073 ÷ 14 mkwh or 0.0521%, while at 144,000,000 it is 1.67% mkwh.

By evaluating other target levels, the trade-off ratios between reliability and target outputs can be calculated for any level of accumulative energy deficit or conversely the trade-off ratio between target level and deficit magnitude increase at any firm level of assurance can be calculated.

Note that there is an objective to minimize the exceedance probability of each and every value of energy deficit. This is a virtually impossible task. However, it can be noted that so long as the decisions considered are the target levels, none of the curves A, B, and C can be expected to cross. Thus, minimization of the exceedance probability at, e.g., 500 mkwh accumulative deficit would also minimize the exceedance probability at all other levels.

On the other hand, if the decision variables are extended to the release strategy during the deficiency, it is possible to minimize the probability of deficit at one level by increasing the probability at another. Normally, this would be counterproductive, unless indeed the increased probability levels were of no consequence to the decision makers.

In most practical cases it may be possible to select a specific deficit magnitude to be used as the index, and utilize only the target level as the decision variable at the planning state. The operational decision on the actual release would then be the separate conditional problem, given an impending deficit of expected magnitude, D; the decision would decide how this deficit should be distributed over time to minimize the adverse consequences of that deficit.

Summary

Despite the importance of assurance or risk minimization, risk has not explicitly been considered as an objective to be minimized in water resource systems analysis. Instead, the standard engineering practice has been to introduce risk implicitly by defining the design yield of a project with a given storage capacity to be the largest yield that could have been obtained with no failure if the past historical record of streamflows were to repeat itself exactly. In this way, risk was implicitly used as a constraint without any actual evaluation of the corresponding level of risk.

If risk is to be considered as an objective in a multiple-objective optimization analysis, a fundamental requirement is the definition of one or more suitable quantitative indices of risk. The methodology developed in this paper provides

the definition of such indices which can be explicitly included in the analysis of water resources systems.

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WRC STANDARD FLOOD FREQUENCY GUIDELINES

By Donald R. Jackson,[1] M. ASCE

INTRODUCTION

In most engineering studies of flood damage reduction measures a key aspect is the determination of the probability of different levels of flooding. The procedures used for the determination of flood probability at a given location depend on whether data are available at that location. If data are available at the location, common practice is to fit an assumed statistical distribution to that data. However, there are a number of statistical and engineering problems involved in determining the appropriate statistical procedures to use.

In order to meet a need for standard procedures for determining flood frequency, the Water Resources Council has provided guidance for the Federal agencies (15,16). In using these guidelines the writer has identified a number of problems which need further study and amplification. The purpose of this paper is to present those problems for further analysis.

The need for standard methodology for flood frequency analysis was recognized by the U.S. Congress (12) when they stated in part:

> The Water Resources Council should establish a panel . . . (which) should be directed to examine methods of frequency analyses with regard to their sufficiency for applying various techniques of flood damage abatement. After this review the panel should present a set of techniques for frequency analyses that are based on the best known hydrological and statistical procedures. It should describe the circumstances in which each method might be most suitable and would delineate the assumptions and consequences that are involved in the use of each. Its report should describe those procedures among the suitable methods which, in its judgment, should

[1]Staff Hydro., Susquehanna River Basin Commission, Harrisburg, Pa. 17102.

Note.—Discussion open until August 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on October 19, 1978. This paper is part of the Journal of the Water Resources Planning and Management Division, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. WR1, March, 1981. ISSN 0145-0743/81/0001-0211/$01.00.

be standardized in Federal Practice. The panel report should be composed in language most helpful to the project engineer.

The writer has long believed that there is a need for standardization of methodology in all branches of hydrology but especially with respect to flood frequency analyses. The need for standardization of flood frequency analyses arises from the following problems:

1. It is not possible to develop comprehensive, coordinated plans for flood damage reduction unless all possible alternatives, including both structural and nonstructural designs, are based on the same flood frequency curve.
2. It is not possible for the Office of Management and Budget or the Congress to compare different requests for project funds, or to make appropriate allocations of the nation's resources for construction of flood control projects unless the economic analyses and flood frequency determinations are made according to established standards.
3. A national flood plain management program including flood insurance is difficult to implement without such standards.
4. When significantly different values for a flood of given exceedance probability at a given location are presented to the public at large the result must be confusion and a feeling that something is wrong. Existence of such different values, which the public must presume to have equal credibility, can only cause the public to question the engineering data and to further question the professionalism of the engineers and agencies involved. The profession can acknowledge the errors and uncertainties inherent in the determination of flood frequency, but such problems can not be explained satisfactorily to a landowner who is about to have development controls put on his land or to a city council that wants a flood control project, preferably at Federal expense. Thus, it seems imperative that the statistical problems be resolved at the professional level.

Note that the need for standardization exists above and beyond the needs of the Federal Flood Insurance Program.

The writer participated in most of the review talks of the Work Group on Flood Frequency of the Water Resources Council which drafted Bulletin 17, and began using the recommendations of Bulletin 17 in carrying out station flood frequency analyses as those recommendations were finalized and prior to the actual publication of Bulletin 17. In the writer's judgment Bulletin 17 is a major contribution to the goal of standardization of flood frequency analyses and a great improvement over its predecessor, Bulletin 15 (17). Bulletin 17 represents the best recommendations possible in terms of the state-of-the-art in May 1974. However, it does have certain limitations and flaws, and the state-of-the-art is bound to change in the future. Thus, the recommendations of Bulletin 17 should not be considered as irrevocable but rather should be considered as subject to change as more data becomes available and as the state-of-the-art changes. The following review of problems encountered in applying Bulletin 17 is offered in the hope of stimulating further analysis and advances in the state-of-the-art.

The major problem areas that have been encountered are: (1) Regional skew coefficient map; (2) detection and treatment of high outliers; (3) detection of

low outliers; (4) weighting of station and regional estimates; and (5) lack of specific recommendations regarding the so-called expected probability adjustment.

Regional Skew Coefficient Map

Bulletin 17 (15) requires that generalized estimates of the skew coefficient of the log-Pearson Type III distribution be used in nearly all cases. Certain recommendations are given for deriving regionalized skew coefficients. Considering the fact that if every user derived his own regional skew coefficients there would be many different skew coefficients for every gaged location (to say nothing of ungaged locations), it appears that a nationwide regional skew map would be desirable (if not essential) if the objective of consistency is to be met. Bulletin 17 includes a regional skew map which is furnished for the use of those who do not want to derive their own regional skew coefficients (which will probably be most users). Unfortunately, the map has become a source of controversy, partly because the state-of-the-art of deriving such maps is not well advanced. As a result of controversy over this map, a new skew coefficient map is being developed for the Susquehanna Basin.

Bulletin 17 recommends certain procedures for deriving a regional skew map. At the time these recommendations were written the procedures seemed satisfactory. However, in the meantime a combination of hindsight and additional experience has suggested the following questions relative to the recommended procedures:

1. There are numerous problems involved with trying to draw isoskew lines for watersheds greater than 1,000 sq miles in size, so some size limitation should be placed on the watersheds used. Parenthetically, the skew map included with Bulletin 17 was derived from station data for watersheds less than 500 sq miles in size. What regional skew coefficient should be used for larger water sheds? This is one objection to the map included in Bulletin 17.

2. The recommendation to use regression was based on the concept that a regression equation would provide an objective, and rational basis, for predicting skew coefficients. It was recognized that previous efforts to develop regression equations for skew coefficients had been unsuccessful. Without disagreeing with the basic logic, it appears that the argument has a hidden assumption that skew coefficients are affected by a (finite) set of watershed factors all of which are known and can be expressed in terms of certain easily obtained paramters. This assumption seems questionable. Firstly, very little is known about factors which affect skew coefficients. In the absence of sound physical concepts regarding the factors which affect skew coefficients, the best way to determine these factors is by regression analyses, which have, until now, been unsuccessful. Secondly, it is known that station skew coefficients are biased, and it is probable that they are affected by chance occurrence of certain extreme events, i.e., outliers. Thirdly, the parameters describing the physical factors which affect skew coefficients may not be the same as those which affect other parameters of the distribution, e.g., the mean.

3. How should outliers be handled in deriving the station skew coefficients used in the regional analysis? No adjustment for outliers was made in deriving

the Bulletin 17 skew map. This is another objection to the map.

4. Should station skews be corrected for bias? Again, no bias correction was made to the station skew coefficients in deriving the Bulletin-17 skew map. If the record length of stations used in deriving a regional skew map are highly variable, it is possible that a significant amount of the variance of those skew coefficients is due to bias. The standard error of the regression equations may also be affected with the result that the regressions appear nonsignificant.

5. What variables should be considered in the regional analysis? Strahler (10) shows schematically the effect of the bifurcation ratio on hydrograph peaks. It is not unreasonable to expect that if the hydrograph peak is so affected, the skew coefficient will be also. However, computation of bifurcation ratios is a tremendous amount of work especially for large watersheds. Also there may be certain parameters that affect skew coefficients that are best expressed using dummy (0,1) variables.

6. There is no mention of consistency of skew coefficient maps across major basin divides. If a new skew map is developed for the Susquehanna basin there is no assurance that the skew coefficients for adjacent watersheds on opposite sides of the divide between Susquehanna and Delaware, Genesee, Allegheny, Monongahela, or Potomac basins, which surround us on the east, north, west, southwest, and south respectively will be consistent. Is such consistency necessary or even desirable?

7. In light of the foregoing comments it may be impossible to derive statistically significant regression equations without considerable additional research on appropriate parameters, and possibly not even then. However, the regression equation can be interpreted as representing deterministic (but not necessarily causal) factors that affect skew coefficients even though the percentage of explained variance is relatively small. Perhaps it would be more profitable to map the residuals from the prediction equations rather than trying to develop prediction equations for the residuals from an isoskew map.

8. How much smoothing should be done when drawing isolines? One objection to the skew map included with Bulletin 17 is that procedures used in deriving that map resulted in too much smoothing. Perhaps the standard error of estimate of the station skew coefficient should be used as a guide to smoothing along with knowledge of each individual watershed when drawing an isoskew line.

9. Matalas, Slack, and Wallis (8), and Wallis, Matalas, and Slack (14) have questioned whether skew coefficients can be mapped. The authors of the latter paper concluded that the problem is due to spatial and temporal mixing of population skew coefficients. The variability of skew coefficients with time has been documented (9,13).

The aforementioned problems also raise certain policy issues that need to be addressed. Firstly, there is some confusion over the interpretation of Bulletin 17 regarding usage of the skew map included in Bulletin 17. Certain parts of Bulletin 17 can be interpreted as requiring use of the skew map included with the report, unless another map has been prepared using Bulletin 17 procedures. Another interpretation is that any regional skew map is acceptable and the only requirement is that a generalized skew coefficient be used.

Secondly there is a question whether a new skew map *must* be derived according

to procedures given in Bulletin 17. If so, there are certain problems, previously mentioned, which are not covered in Bulletin 17, but which will inevitably arise in deriving a skew map. In the absence of further guidance on these points it is difficult to derive a new skew map. Conversely, it may not be possible to give further guidance without additional research designed to develop the technology. Thus, we have an impasse. Alternatively, it may be possible to derive the skew map for a limited area, using alternatives to Bulletin 17 procedures, or expanding on those procedures, or both, and demonstrating the reasons for departure from Bulletin 17 procedures. This will aid in developing more complete procedures.

Thirdly, what mechanism should be established to review and approve a new skew map(s)? Can the problem be handled at a regional level or must it be referred to the Hydrology Committee?

In response to these questions, the Hydrology Committee (personal correspondence) has stated that the Bulletin 17 skew map is considered acceptable if an individual study has not been made. The statement that the map is acceptable implies that it is not required. In response to the second question the Hydrology Committee has stated that procedures other than those given in Bulletin 17 may be used if supported by appropriate study and comparison with the results obtained using the recommended procedures. However, certain of the aforementioned questions are not addressed in Bulletin 17, therefore no comparison can be made. In response to the third question, the Hydrology Committee has endorsed a coordinated study effort at the regional level to develop a regional skew map.

In the Susquehanna basin an interagency cooperative study is underway to derive a new regional skew map. While it is desirable to use the best possible statistical techniques in deriving regional skew maps, it may be that the best regional skew map is the one that is acceptable to all agencies in that region, and not one that can be shown to be statistically best.

Detection and Treatment of High Outliers

A major flaw in Bulletin 17 is the absence of any criteria for the detection of high outliers. The problem is to determine an appropriate criterion for determing which events are high outliers.

In the absence of further guidance, the following criterion seems reasonable and practical. If the event plots above the upper 5% one-sided confidence limit about the curve fitted with the event included, the event should be treated as a high outlier in accordance with Bulletin 17 recommendations. The confidence limit is computed using the procedures outlined in Appendix 9 of Bulletin 17.

Another problem which has arisen is the question of an appropriate record length for the high outlier. In general, systematic peak flow data are not available in our basin prior to 1937 except along the main rivers. In a number of cases local newspapers or long time residents have been requested to furnish information on pre-record floods. The minimum information required is whether the water was previously as high as during, e.g., the 1972 flood. In general, that information is not readily available for tributary streams, without fairly extensive field work.

However, it is generally known when the major floods occurred in a particular area and it is possible to compare rainfall amounts for different storms on

a watershed in question. Generally, that will show, e.g., that the 1972 flood was greater than floods of 1964, 1945, 1936, and 1889 even though we may have data only for, say 40 yr at the site. From such analysis we may conclude that the 1972 event is typical of an historical period going back to, say, 1889. Occasionally different historical record lengths will be assumed and a judgment made as to which resulting flood frequency curve looks best. This is obviously not very scientific but it appears to produce reasonable results.

Detection of Low Outliers

It is well known that the log-Pearson Type III distribution has an upper bound if the skew coefficient of the logarithms is negative, and a lower bound if

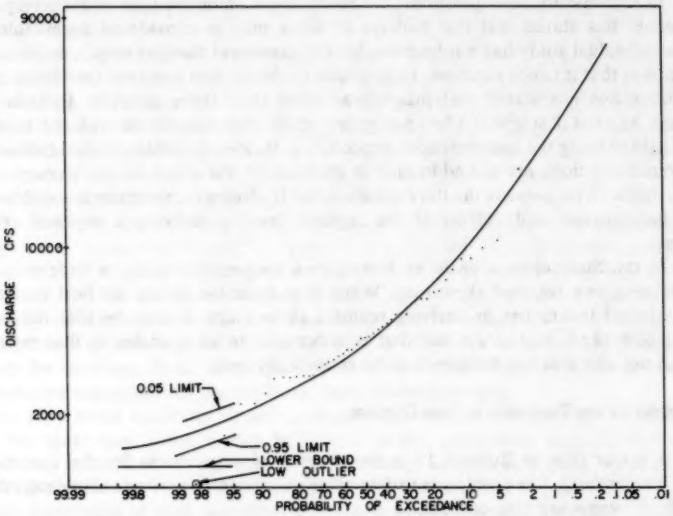


FIG. 1.—Example of Low Outlier below Lower Bound (Station Number 01555500)

the skew coefficient of the logarithms is positive. It would seem logical that flood peaks that lie above or below these bounds based on the moments computed with all events included in the sample, should be rejected as outliers because they can not logically be part of the distribution. A major problem experienced with the low outlier detection criterion is that events that are below the lower bound of the log-Pearson Type III distribution are not rejected. One example is shown in Fig. 1. The lower bound can be determined visually or computed from the equations derived by Gilroy (5).

The important point is the fact that there are cases in which at least one annual peak is less than the lower bound but that annual peak is not rejected by the Bulletin 17 low outlier test. Since such a point can not logically belong

to the fitted distribution the frequency curve should be recomputed without those values, and the probabilities adjusted as examined in Appendix 4 of Bulletin 17.

Weighting Station and Regional Values

Appendix 8 of Bulletin 17 suggests a procedure for adjusting flow frequency estimates based upon short records to reflect flood experience in nearby hydrologically similar watersheds. The basic concept is that if two independent estimates are weighted inversely proportional to their variances, the variance of the weighted average is less than the variance of either estimate. The assumption is then made that estimates computed from a regional flood frequency are independent of the station estimates, even if the station estimate is used in deriving the regional equations. That assumption is obviously false in theory, and it has not been verified in practice.

The important equation to consider is the following (which is Eq. 8-2 in Bulletin 17)

$$V_z = \frac{V_x V_y}{(V_x + V_y)^2}(V_x + V_y + 2r\sqrt{V_x V_y}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which V_x and V_y = the respective variances of the two independent estimates, x and y; r = the cross correlation between values of x and values of y; and V_z = the variance of the weighted average. The question to be evaluated is whether the weighted average can ever have a greater variance than the station data only. This is equivalent to finding the value of r such that

$$V_x < V_z = \frac{V_x V_y}{(V_x + V_y)^2}(V_x + V_y + 2r\sqrt{V_x V_y}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In the Appendix I of this paper it is shown that if the variances are inversely proportional to record length, the foregoing condition will be satisfied if

$$r > \frac{1}{2\sqrt{C}}\left(\frac{C+1}{C}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which $C = N_x/N_y$; N_x = the station record length; and N_y = the effective record length of the regional regression. Eq. 3 is solved for selected values of C in Appendix I. For example, if $N_x = N_y$ the variance of the weighted estimate is always less than the variance of the station estimate. Similarly, if $N_x = 1.5N_y$, the variance of the station estimate will be less than the variance of the weighted estimate if the correlation is greater than 0.68.

Hardison (6) has independently derived a similar equation, but the results are presented in a somewhat different fashion.

There may be some question as to what the correlation coefficient, r, represents. The concept used to derive Eq. 1 is the customary formula for the variance of a sum of values. If (4)

$$y = \sum_{i=1}^{m} a_i x_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$\text{var}(y) = \sum_{i=1}^{m} a_i^2 \,\text{var}(\mathbf{x}_i) + 2\sum_{i<j} a_i a_j \,\text{cov}(\mathbf{x}_i, \mathbf{x}_j) \quad \ldots\ldots\ldots\ldots\ldots (5)$$

The correlation coefficient of course arises in representing the covariance of $\mathbf{x}_i$ and $\mathbf{x}_j$. In our case $\mathbf{x}_i$ = the vector of discharges at a specified return period from the station flood frequency curve from m stations in a given region, and $\mathbf{x}_j$ = the vector of discharges computed from a regional analysis at the same sites. Then the correlation coefficient is given by

$$r = \frac{\sum_{i=1}^{m} (Q_{pi} - \bar{Q}_p)(\hat{Q}_{pi} - \bar{\hat{Q}}_p)}{\left[\sum_{i=1}^{m} (Q_{pi} - \bar{Q}_p)^2 \sum_{i=1}^{m} (\hat{Q}_{pi} - \bar{\hat{Q}}_p)^2\right]^{1/2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

in which Q_{pi} = the value of the discharge at probability, p, from the station flood frequency curve for the ith station; and $\hat{Q}_{pi}$ = the value of discharge at probability, p, estimated from the regional procedure, also for the ith station.

It seems obvious that the correlation coefficient can be computed for a set of stations chosen in any desired fashion as long as the regional equation applies to all the stations so that $\hat{Q}_{pi}$ can be computed for all the locations using the regional procedure.

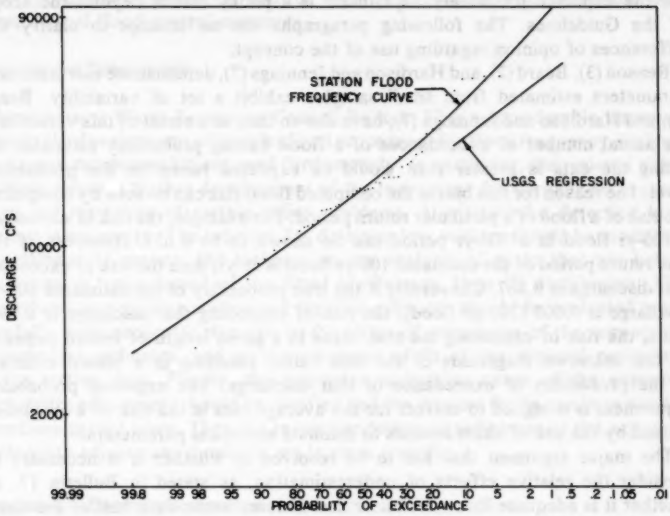
W. O. Thomas (personal correspondence) notes that these values would tend to be correlated even if independent estimating techniques were used. There may be a semantic argument involved with respect to the meaning of independence. In statistics, it is commonly stated that if two random variables are independent they are uncorrelated (4). From mathematical logic the contrapositive of that proposition is that if two variables are correlated they are not independent, and the contrapositive is always true if the proposition is true (1). Thus, the only way to show that two variables are uncorrelated is to show that the population correlation coefficient is zero. If it is not, the variables cannot be independent. Anything else is an approximation. Thus, there cannot be any two "independent" estimating procedures unless the two procedures produce results with such highly variable estimates of Q that r is small. Otherwise, the resulting estimates are not independent and the correlation term in Eq. 4 must be included under all conditions.

There is a major problem with using this weighting concept. In a regression analysis the objective is usually to develop the best possible equation (within certain constraints) that generally means that the equation has a low standard error of estimate. If the equation has a low standard error of estimate, the correlation coefficient, r, computed by Eq. 6 should be large. But if r is too large the weighted estimate has larger variance than the station estimate alone. The problem is further compounded by the relationship between the standard error of estimate and the effective record length of the regression equation. Thus the objectives of the weighting procedure and of the regression analysis used to derive the regional estimates tend to be internally contradictory.

An example of the computation of the correlation coefficient is beyond the scope of this paper. However, it seems desirable to compute correlation coefficients for each hydrologically homogenous region and to compare the

computed values to the aforementioned critical values before the weighting procedure is used.

Another question is whether the weighting procedure should be used in cases where the regional procedure does not fit the station data. One example is shown in Fig. 2. One opinion is that the regional procedure should always be weighted with the station results on the basis that the station curve is biased due to time sampling error, and the regional procedure removes some of that bias. However, that assumption seems valid only if the watersheds used in the regional regression are sufficiently homogeneous in all hydrologic parameters to consider them as one sample. This implies a perfect correlation between flood peaks in the region that occurs only for a sample coincident in time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STATION FLOOD FREQUENCY CURVE
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PROBABILITY OF EXCEEDANCE

FIG. 2.—Example of Poor Fit of Regional Regression to Station Data (Station Number 01552000)

and having nearly the same watershed parameters. The assumption seems invalid for a regional procedure that is based on watersheds with variable record lengths, where stratification of the sample is based on examination of residuals, or where the watershed size (and perhaps other parameters) varies by more than one order of magnitude.

The aforementioned criteria are not easy to apply operationally. An alternative recommendation is that the weighting of station and regional estimates should be used only if the regional estimate provides a satisfactory fit to the station curve, and then only if the record lengths and regional correlation coefficient satisfy the conditions required for $V_z < V_x$. However, criteria are necessary to determine whether the fit of the regional equation to the station curve is

satisfactory. In the absence of such criteria, an individual judgment becomes necessary, which tends to promote lack of uniformity.

Expected Probability Adjustment

There appears to be considerable controversy regarding the so-called expected probability adjustment and its use. Some people believe that the expected probability adjustment is simply a safety factor applied to the flood frequency curve. Others consider it to be a refinement of the flood frequency curve, and that philosophy underlies the Bulletin 17 discussion. Part of the problem is semantic in that the terminology used is open to misinterpretation.

As a result, it is stated in Bulletin 17 that the determination of whether to use the expected probability adjustment is a policy matter beyond the scope of the Guidelines. The following paragraphs are an attempt to clarify the differences of opinion regarding use of the concept.

Benson (3), Beard (2), and Hardison and Jennings (7), demonstrate that statistical parameters estimated from small samples exhibit a lot of variability. Beard (2), and Hardison and Jennings (7), have shown that, as a result of this variability, the actual number of exceedances of a flood having probability estimated by fitting the data is greater than would be expected based on the probability level. The reason for this bias in the computed flood risk can be seen by computing the risk of a flood of a particular return period. For example, the risk of exceeding a 100-yr flood in a 100-yr period can be shown to be 0.634. However, if the true return period of the estimated 100-yr flood is 50 yr, then the risk of exceeding that discharge is 0.867. Conversely if the true probability of the estimated 100-yr discharge is 0.005 (200-yr flood), the risk of exceeding that discharge is 0.394. Thus, the risk of exceeding the true value in a given length of record depends on the unknown magnitude of the true value, resulting in a biased estimate of the probability of exceedance of that discharge. The expected probability adjustment is designed to correct for the average bias in the risk of exceedance caused by the use of short records to estimate statistical parameters.

The major argument that has to be resolved in whether it is necessary to consider the relative effects of underestimation, as stated in Bulletin 17, or whether it is adequate to overestimate and underestimate each half of the time. Thomas (11), has pointed out that the median of the estimates of the probability of exceedance from many short samples is close to the long record estimate of the exceedance probability while the mean of the probability estimates is somewhat greater than both the median and the true estimates. The fact that the mean of the estimates of the probability of exceedance is greater than the true probability is the basis for the expected probability adjustment. Conversely, the use of the median estimate implies that it is adequate to simply overestimate half the time and underestimate the other half of the time. Thus, the argument can be phrased as follows: For hydrologic engineering purposes should the mean estimate of probability of exceedance or the median estimate of that probability be used? The answer to the question should be based on expected value analysis of project economics using a national income accounting point of view. Such analyses have been made by Beard (2), and by Hardison and Jennings (7), and support the use of the mean probability of exceedance. A more general analysis may be desirable.

As a result of the recommendation incorporated in Bulletin 17, the major agency involved in structural flood control planning and the major Federal agency involved in nonstructural flood control planning have adopted opposite policies regarding use of the expected probability adjustment. As a result of the design and economic analysis of many local flood protection projects will be based on a flood frequency curve that includes the expected probability adjustment, while nonstructural flood protection projects for the same locality will be based on a flood frequency curve that does not include the expected probability adjustment. Obviously, this difference in flood frequency curves does not promote the standardization of flood frequency methodology that is the objective of Bulletin 17. It makes it more difficult for a regional water resource planning agency such as the Susquehanna River Basin Commission to develop comprehensive, coordinated joint flood control plans incorporating both structural and nonstructural flood control measures.

Summary and Conclusions

In summary, Water Resources Council Bulletin 17 is a considerable improvement in the development of standardized procedures for flood frequency analysis but certain recommendations need further study. In particular, the regional skew problem requires further development of the technology for deriving such skew maps and resolution of certain policy problems. A criterion for detecting high outliers is necessary. The criterion for detecting low outliers should be modified, in particular to prevent the inclusion in the analysis of peaks that are below the apparent lower bound of the fitted log-Pearson Type III distribution. The procedure for weighting station and regional estimates should be evaluated more carefully, with particular attention to the effect of correlation of the supposedly independent estimates, and to the goodness of fit of the regional procedure to the station data. Finally, the principles underlying usage of the expected probability adjustment should be clarified and the reasons for its use in particular situations agreed upon. Then the recommendation regarding use of the expected probability adjustment should be made more specific.

Appendix I.—Effect of Correlation on Variances of Weighted Sum

Consider Eq. 1 which is the same as Eq. 8-2 in Water Resources Council Bulletin 17. Assume that the respective variances are inversely proportioned to the effective length of record. Then

$$V_x = \frac{K}{N_x} \quad \ldots\ldots\ldots\

$$V_z = \frac{\frac{K}{N_x}\frac{K}{N_y}}{\left(\frac{K}{N_x}+\frac{K}{N_y}\right)^2}\left(\frac{K}{N_x}+\frac{K}{N_y}+2r\sqrt{\frac{K}{N_x}\frac{K}{N_y}}\right) > V_x = \frac{K}{N_x} \quad \ldots\ldots (9)$$

$$\frac{K}{N_x} < \frac{K}{N_x N_y\left(\frac{1}{N_x}+\frac{1}{N_y}\right)^2}\left(\frac{1}{N_x}+\frac{1}{N_y}+2r\sqrt{\frac{1}{N_x}\frac{1}{N_y}}\right) \quad \ldots\ldots (10)$$

$$\frac{1}{N_x} < \frac{N_x+N_y+2r\sqrt{N_x N_y}}{(N_x+N_y)^2} \quad \ldots\ldots (11)$$

Let $C = \frac{N_x}{N_y}$ $\ldots\ldots (12)$

$$\frac{1}{CN_y} < \frac{N_y(C+1+2r\sqrt{C})}{N_y^2(1+C)} \quad \ldots\ldots (13)$$

$$\frac{1}{C} < \frac{C+1+2r\sqrt{C}}{(1+C)^2} \quad \ldots\ldots (14)$$

$$r > \frac{1}{2\sqrt{C}}\left(\frac{C^2+2C+1-C^2-C}{C}\right) \quad \ldots\ldots (15)$$

$$r > \frac{1}{2\sqrt{C}}\left(\frac{C+1}{C}\right) \quad \ldots\ldots (16)$$

Solve Eq. 16 for selected values of C:

C	$[1/(2\sqrt{C})]\,[(C+1)/C]$
1.0	1.0
1.5	0.680
2.0	0.530
3.0	0.385
4.0	0.313
5.0	0.268

If $C > 1.0$, $[1/2\sqrt{C})]\,[(C+1)/C] > 1$ which is not a feasible region for the correlation coefficient. As C increases (i.e., the effective record length of the station data increases relative to the effective record length of the regional equation), the critical value of r decreases. For example, assume that the effective record length of the regional procedure is 20 yr. Then if the effective record length of the station data is 30 yr, $C = 1.5$, and the variance of the weighted sum will be greater than the variance of the station value if the correlation coefficient $r > 0.680$.

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Appendix III.—Notation

The following symbols are used in this paper:

a_i = dummy coefficient;
C = ratio of effective length of station record to effective length of regional procedure;
i = dummy index of summation;
K = dummy constant of proportionality;
m = dummy variable of summation;
N_x = effective record length of annual peaks at station;
N_y = effective record length of estimated peak discharge from regional procedure;

Q_{pi} = peak flow rate of probability p from flood frequency curve for ith station in region;
$\bar{Q}_p$ = mean of values of Q_{pi} for m stations in region;
$\hat{Q}_{pi}$ = peak flow rate of probability p estimated from regional procedure at ith station in region;
$\bar{\hat{Q}}_p$ = mean of values of $\hat{Q}_{pi}$ for m stations in region;
r = correlation coefficient;
V_x = variance of estimates of peak flow of specified probability based on station data;
V_y = variance of estimates of peak flow of specified probability based on regional procedure;
V_z = variance of weighted average of two random variables;
y = weighted sum of random variables $\mathbf{x}_i$; and
$\mathbf{x}_i$ = dummy vector of random variables.

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PERSPECTIVES ON WATER CONSERVATION

By the Task Committee on Water Conservation
of the Water Resources Planning Committee
of the Water Resources Planning
and Management Division

FOREWORD

The work of this committee began with the task of preparing a state-of-the art report on water conservation practices. It became apparent in the early stages of its work that such an objective would be difficult to achieve for a number of reasons. First, water conservation is not an objective in itself, but is part of the broader objective of total water management. As such, conservation should be placed in perspective relative to many other considerations. Second, in most regions water is a renewable resource. Unlike fossil fuels, water is a replenishable resource; supplies become plentiful during wet periods, and scarce during dry periods. Third, the committee recognized that the purpose, method, and level of water conservation is site specific, and will depend on a number of factors. This latter, in itself, considerably broadens the scope of any effort to prepare a technical discussion on conservation practices. Lastly, while water conservation is a national policy, the committee recognized that a professional understanding of the full implications of conservation in an engineering, economic, social, and environmental sense is just emerging for some measures, and may be years away for others. This is to say that as a society and as a profession we are just beginning to learn about water conservation and its implications for resource management.

Members of the task committee have maintained liaison with other groups—primarily within the Federal government—working on similar projects. The committee's work has been provided to the ASCE Committee on National Water

Note.—Discussion open until August 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on May 1, 1980. This paper is part of the Journal of the Water Resources Planning and Management Division, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. WR1, March, 1981. ISSN 0145-0743/81/0001-0225/$01.00.

Policy for use in preparing an ASCE statement for Congressional hearings on National water policy proposals.

Throughout the initial phases of its work the task committee noted many areas of water conservation in which our knowledge of technology, impact assessment, and plan evaluation is insufficient to permit rational comparison of water conservation alternatives with alternatives involving the development of new water supplies. The life of the task committee has been extended to permit further examinations of some of these areas.

Members of ASCE who are interested in the subject of water conservation are encouraged to read the task committee's initial report and provide their thoughts in the form of discussions for publication in this journal. Throughtful discussion will contribute significantly to the work of the task committee during the next phase of its work.

What is Water Conservation?

Yesterday.—To Gifford Pinchot, W. J. McGee, Francis Newlands, and others during President Theodore Roosevelt's administration, water conservation meant the construction of reservoirs to *conserve* spring flood waters for use later in the dry season. Lands in the west needed water for irrigation and water storage reservoirs were one way to meet this need. McGee wrote in 1906 concerning Federal development of water resources (1):

> Thus far the greater part of the operations have been in the area of interior or Pacific drainage, though extensive works have been located in the westerly portion of the Mississippi basin. They are primarily to *conserve* storm-water and convey them to lands requiring irrigation: yet incidently they reduce storm-floods and thaw-freshets, and retain much of the contained sediments.

Later through Roosevelt, Pinchot, and others the meaning of water conservation expanded to include the ideas involving multiple-purpose river development (2):

> . . . they interpreted conservation in the broadest possible sense to include the best utilization of the country's eternally replenishing water resources through comprehensive programs of multiple-purpose undertakings for navigation, power, and other beneficial uses.

This concept for utilizing the nation's water resources was the impetus for water development during the first half of this century. "Wise use" was the conservation "ethic" of that period; water was recognized as a renewable and reusable resource.

Today.—Now frequent reference is made to more efficient use of existing water supplies, to water reclamation, and to reducing unit consumption. Water managers are beginning to recognize the value of instream uses and the value of freshwater flowing to the sea. Today's view of the interconnection of systems and the limits to system carrying capacities—water supply, waste disposal, energy, rivers, estuaries, and the environment—coupled with a technological ability to intrude upon and modify natural systems are some of the basic causes of the

evolution in the meaning of water conservation.

Dr. Luna Leopold, has expressed the following (3):

> (I)n the face of the obvious limitation of resources, whether renewable or nonrenewable, continued and indefinite expansion of resource use is patently impossible. Some movement toward a steady state condition that lies within the bounds of resource availability is not only the crux of a resource management philosophy, but is the acid test of leadership. I do not consider this politically impossible. The public is learning. It may well be the best political course to pursue.

President Carter, in announcing his new Water Policy in June 1978, indicated that water conservation was to be the cornerstone of this nation's management of water supply systems in the future. In the implementation of that policy, the following statement was adopted by the Administration (4):

> . . . water conservation should consist of proposed changes that will (a) reduce the demand for water; (b) improve efficiency in use and reduce losses and waste; and (c) improve land management practices to conserve water . . .

Whether one views water conservation as storing spring runoff, minimizing waste, or reducing demand, each is only part of total water management. While time and social conditions have changed the meaning of water conservation, it still remains only part of the whole. Water is a renewable and reusable resource and future water needs will be met best by looking at all aspects of both supply and demand and selecting those means or measures which are most appropriate for the conditions considered.

Why Water Conservation?

A variety of reasons are offered for adopting water conservation using today's definition of demand reduction. They vary depending upon local water supply needs, the attitude of local citizens, management attitudes of water districts, economics, and existing laws and regulations. Some of the specific reasons offered include to: (1) Increase available water supply and defer capital expenditures for new or expanded facilities at specific locations; (2) reduce energy consumption through less pumping, processing, or heating; (3) reduce wastewater flow to reduce treatment costs and energy use; (4) make existing supplies stretch further where new supplies are not available, or are limited in quantity, or are restricted by legal rights; (5) meet Federal, state, or local requirements; (6) insure that an existing water system is not wasteful; (7) be responsive to conservation ethics held by the public or by public leaders; and (8) buy time to finance or construct water and sewage plants.

Where to Conserve?

In 1976 and 1977, California experienced its worst drought on record. Prior to, and during this period, many pioneering efforts were developed to use less

water in municipal, industrial, and agricultural use. The most viable of these responses could serve as planning models for water conservation. The programs initiated fell into two classes: those which are appropriate during emergency conditions and essentially of a limited duration, and those which are part of the conservation "ethic" which are intended for constant use. Emergency response programs and "normal" conservation programs are essential parts of planning for effective use of limited resources. The level of conservation planning, its specifics, and the specifics of an emergency response program will vary with the geographic area, resource availability, the nearness of supplemental sources of water, and the economic and employment development in the area. Additionally, initial steps of an emergency response program might also be included as part of a "normal conservation program.

Emergency Programs.—Emergency response programs generally increase savings, and are tied to the severity of the emergency condition. The problem during drought is to properly manage available resources. Emergency programs generally consist of: (1) Restrictions on nonessential use; (2) utilization of interconnection systems, if available; (3) restrictions on public use; (4) restrictions on industrial use; (5) restrictions on domestic use often coupled with significant charges for not meeting the limits imposed; (6) increased withdrawals from undergound basins; (7) reducing the acreage of irrigated farm land planted; (8) changing agricultural cropping patterns; and (9) increasing agricultural water use efficiency. An emergency program will focus on who will be hurt by the shortage and the economic consequences. For example, in municipal systems, assuming adequate supplies are available for subsistence, there will be a strong desire to preserve jobs which means special consideration to economic impacts. While a municipal program may impose "mandatory" restrictions, the experience in many California communities was that they were really voluntary because of the lack of enforcement capability. Three requirements of an effective voluntary program are that: (1) Adequate information be made available on what to do; (2) the consumer clearly perceives the need; and (3) there be ample media coverage.

Normal Conservation.—Normal conservation, that which can be implemented without significant changes in existing life styles, consists generally of a combination of the following:

1. Use of home conservation devices in new construction. (The state of California now requires water-saving toilets in all new construction.)
2. Promotion of reuse, both indirect and direct. Indirect reuse is now in practice in many areas although many people are generally unaware of this. Direct reuse is not widely practiced, except in isolated areas where other options are very limited. Recycling, on the other hand, is widely practiced in the industrial sector.
3. Promotion of good operation practices, including the elimination of leaks. Identification of leaks and repairs can in many areas result in significant savings. Leak repair, however, is a costly operation if not part of a utility's normal operation program.
4. Development of a public education program to promote the conservation ethic.
5. Increasing the level of sophistication in agricultural water management.

Who Should Conserve?

Who conserves is a significant issue in that it determines the amount conserved, the source from which the supply is conserved, the region affected, and the means and measures used. Is it the user or the purveyor? Is the purveyor public or private? Is the user municipal, domestic, commercial, industrial, or agricultural? Does the water being conserved originate from a reservoir, river, or ground-water aquifer? A distinction must also be made between who will conserve during an emergency situation and who will conserve as part of normal conditions. In a recent drought in England where strict rationing was necessary in many places, preference was often given to industry in order to maintain employment, and the production of necessary foods and electrical power.

In California during the 1976–1977 drought, conservation measures were directed toward both urban and agricultural users. Many urban users were dependent upon surface water supplies and were encouraged to reduce usage by voluntarily using less water and by controlling usage through household water-saving devices. Conservation by agricultural interests was encouraged through reducing unauthorized diversions, enforcement of water rights, and voluntary pro rata sharing of loss. Farmers also responded by reducing cropped acreage or changing cropping patterns to less water-consuming crops. Unfilled agricultural demands were met by drilling 20,000 new wells, in some cases creating an additional overdraft on the ground-water aquifer and increasing energy pumping requirements until the lowered water level is raised.

Incentives.—Incentives are necessary to encourage conservation, and their existence or nonexistence is likely to determine who will undertake water conservation measures and programs. The two principal incentives are economics and ethics—or some derivative of them. Economic savings may result directly from less use of the water itself or indirectly through savings in energy, labor, or other resources. Ethical incentives are propagated through attitudes and behavior that result in reducing waste and conserving limited supplies.

Municipal conservers can often find a direct benefit from conservation programs through a lower cost of operation of sewerage and waste treatment plans, reduced energy costs, and a deferral of investment to expand water supplies. Important impacts on in-stream values and wildlife habitat have no effective way to be brought into the decision-making process. New institutional arrangements through financial incentives to potential conservers or through rules, regulations, and permits need to be developed, but the trend seems to be the other way toward enhancement or protection of in-stream values.

If an individual or agency cannot see some benefit from implementing measures that increase the efficiency-in-use, then the incentives for conservation are reduced. Often, legal barriers need to be removed so that those who are truly salvaging waste water, or are "saving" water, or both, can reap the benefits of their action. Reduction in in-stream uses or uses for wildlife habitat maintenance can make more water available for traditional economic uses such as agriculture, domestic, commercial, and industrial demands.

Industrial users are sensitive to economics and usually can find ways to reduce water use if costs increase. If an industry purchases water from a public purveyor and discharges wastes to a public sewage system, the industry will be encouraged

to seek savings in water use both from the cost of water supply and from the user charge for wastewater treatment.

Where to Conserve?

Variability of Supply.—Annual precipitation in the United States can vary widely from region to region and even within regions. Humid areas are not only those with more precipitation than arid and semiarid areas, but the variation of annual precipitation from the average is usually less pronounced. For this reason, water systems in humid regions often are constructed with less reserve capacity relative to the average demand than systems in arid regions. While water conservation has the same meaning of reducing the demand for water for both humid and arid regions, those technologies which affect peak demand will be of greater interest in humid areas, whereas technologies that reduce both peak and average usage will concern water managers in the drier parts of the country.

An additional consideration in arid regions is the recognition that there will always be a natural deficiency of water. Additional increases in demand, whether for population or resource development, may exceed the region's natural supply capacity. It is especially important in these regions not to reduce the buffer in storage provided by the ground- and surface water resources. Also, supply components may include supplies of widely varying reliability and this should be considered when incorporating conservation measures into total water management for the region.

In addition to climatic variability of supply there is variability of sources. Several examples illustrate this point:

1. Some systems depend entirely upon stored surface water for their supply. Marin Municipal Water District (in California) is an example. Conservation or reduced demand in this case means that more water will be in storage during drought years, and there will be more runoff going unused during above-normal flow years.
2. Other systems depend almost entirely upon rivers as their source. Philadelphia, New Orleans, and Sacramento are three examples. Upstream use, downstream use, and in-stream flow needs are important considerations for any conservation program for these systems.
3. Ground water is a sole source in many parts of the country. In Albuquerque, N.M., ground water is the sole source for the municipal system. Generally, ground-water supplies are not immediately affected by surface water shortages, and overdrafts in years of drought may be replenished during wet years. A conservation program for this type of supply system should take these factors into account.

Variability of Use.—Water use varies with different regions of the country and within regions. The west withdraws large quantities for agricultural irrigation, the east relatively little. The eastern United States, on the other hand, withdraws most of its supply for cooling at stream electric generation plants, the western United States withdraws relatively little. Domestic and commercial use does not vary as much by region as by center of population. In California, the Los

Angeles and San Francisco Bay areas are the major consumers of water for domestic and commercial purposes. On the east coast, the Boston, New York, and Washington, D.C. areas are major users.

Similar variability exists for other uses: manufacturing, industrial, instream, and offstream.

Not only does the type of use vary geographically, but for each use the amount withdrawn and the amount consumed varies. For example, of the water withdrawn for stream electric generation, less than 2% is consumed. In irrigated agriculture, an estimated 55% is consumed (5).

This variability in use influences the type of conservation program adopted in each region. A program for agricultural water conservation would be especially appropriate for the west and midwest where large quantities of water are withdrawn for irrigation. Yet, even within these broad regions the specific measures would have to be compatible with local farm practices and water laws. Conservation in areas with large withdrawals and return flows would be accomplished by a somewhat different program. In-structure domestic and commercial use would be quite similar in different regions since the infrastructure is similar, although the reason for water conservation may vary depending upon local conditions. Outside use varies with climate. For example, lawn irrigation is much greater in some arid regions than it is in humid regions.

How is Water Conserved?

Total water management involves the conservation of both supply and demand. Supply is conserved through utilization of excess runoff and through efficient distribution. Demand conservation means reduction in usage through education, management, and technology.

Conservation of Excess Runoff.—The principal means of conserving excess runoff is through reservoir storage, storage for ground-water recharge, and interbasin transfers. Reservoir storage has been the traditional means of storing runoff for supply purposes. Storage of excess runoff in ground-water basins has been practiced in some regions; however there is a need to better understand the methods of artificial recharge and their effect. Conjunctive use of ground- and surface water sources is likely to play a much greater role in conservation of supply in the future. Interbasin transfers afford the opportunity to conserve supply in one region for transport to another. Transfers have beome necessary in the past because population growth has taken place in regions which have inadequate supply. To the extent that local supply is inadequate, whether because of population needs or for development of natural resources such as coal, interbasin transfers are a means of meeting water needs.

Efficient Supply Distribution.—Improved efficiency in reservoir system operation, reallocation of storage in existing reservoirs, and reduction of waste in distribution systems all afford an opportunity for conservation of supply. While changes in operating rules and reallocation of storage may require changes in legal and administrative rules, a reexamination of present sources of supply may be worthwhile in light of today's priorities for water use.

Elimination of waste in municipal distribution systems can effect savings in supply. To do this requires continued surveillance and maintenance of the system. In Chicago, leakage is reduced through reduction in pressure incorporated in

the system design. While this may not be possible in many existing systems because of fire requirements, it may be possible in new system design. Also, covering open reservoirs on the distribution system, often those containing filtered water, has been done to protect quality. It has the added value of reducing evaporation.

Likewise, seepage losses in agricultural distribution systems can be controlled by lining canals or using pipelines. In cases where seepage is to a ground-water basin which can be used conjunctively, seepage may be a desirable objective. Where seepage is to a high water table, which is detrimental to crops, the alleviation of such damage will supplement the water conservation objective.

Demand Reduction Through Education.—Education via the news media, literature, and pulic meetings can produce a conservation consciousness as a continuing means of demand reduction. Education programs have been developed in numerous cities across the country. Those in the Marin and North Marin Water Districts of California, the South Florida Water Management District, and the Washington Suburban Sanitary Commission in Washington, D.C. are three examples. Emergency programs developed in many communities in California during the 1976–1977 drought are no longer in effect, but have given way to an ongoing conservation education program. Education, to be most effective, should be geared to the elementary and secondary school level—it is apparently much less effective for long-term benefits at the adult level. The state of California maintains a continuing education effort and also assists local water managers and schools in developing their own programs.

Demand Reduction Through Management

Municipal Use.—Changing the water rate schedule or increasing water rates are controversial means of reducing water use and promoting conservation. Changing from a flat rate schedule to a decreasing or increasing block rate requires metering if it does not already exist. The cost effectiveness of meter installations and reading is now being debated in the water industry. Too frequently with metering a decreasing block rate has been used where unit cost tends to become constant with larger uses. A constant unit rate, where unit cost is directly proportional to quantity, or an increasing block rate where unit cost increases with quantity, can promote water conservation.

In recent years, several communities have changed their rate schedule to encourage conservation. Elmhurst, Ill. is a community which changed its schedule from a declining block rate to a constant rate. The Washington Suburban Sanitary Commission changed from a constant rate to an increasing block rate.

Where water costs account for a relatively small proportion of utility or other household costs it may be necessary to make a rather substantial rate increase before the economic incentive is sufficient. Nevertheless, a schedule of increasing rates with increasing use is consistent with the idea of conservation.

In addition to changes in water rates, other management measures which have been used include: enactment of plumbing and building codes which require water-saving plumbing fixtures and appliances, and land use regulations and growth limits to reduce or control system demand. Reductions in urban water use which directly affect sanitary sewage flow are usually justified on the basis of reduced loadings on sewer systems and wastewater treatment facilities.

Industrial Use.—Federal regulations to clean up wastewater discharges have

been the principal impetus for demand reduction by industry. Management commonly utilizes water reuse, recycling (internal reuse), and water use reduction measures to reduce demand. The main factors affecting the potential for industrial wastewater reuse are availability, economics, reliability, and water quality. For a reuse project to be economically practical the cost of reusing wastewater must not be greater than that of obtaining water from natural water sources or public water supplies. In addition, the wastewater effluent must provide a reliable water source capable of satisfying the industrial water demand at all times. These factors are dependent on the specifics of each prospective reuse operation.

Although wastewater reuse may be technologically and economically feasible, reuse does not necessarily affect demand for public supply. Basically, wastewater reuse will affect public water supply only if the reuse of the wastewater effluent frees a source which could be used for public supply purposes. An example of this would be where an industry now obtains water from a public water supply and switches to reusing a wastewater effluent. In this case, the reduced industrial demand for public water would release water for public supply. Another less obvious example could occur where an industry using a fresh surface water source for nonconsumptive purposes switches to reusing a wastewater effluent. In this case, the quantity of water in the stream would remain the same, but the quality of the surface water would be improved by the removal of the wastewater discharge. If the quality improvement allows a previously unsuitable water source to be used for public supply purposes, then the reuse of wastewater has, in effect, enabled development of additional water for public supply. In the aforementioned examples, specific in-stream uses which are also a "public supply" were not considered.

Agricultural Use.—Since irrigation is by far the greatest consumptive user of water, especially in the west, the potential for making new water available through water conservation is the greatest. The most effective means of making new water available is to reduce water requirements for plant growth. This, however, is very difficult since evapotranspiration for optimum yields for specific varieties of plants is relatively fixed. There are opportunities to reduce surface wetting, use short growing season varieties, or to substitute crops with lower water requirements for those of higher requirements. However, there are limitations to this latter approach since complex socio-political-economic forces usually dictate what a farmer will grow. There are some cases where use of water of lesser quality may aid in the overall conservation effort since some crops are "salt-tolerant."

Since all water supplied to agriculture in excess of its "use" by evapotranspiration may be thought by someone to be a "loss," the various "losses" should be evaluated. There is a large group of "losses" that are recoverable for other uses (one person's loss is another person's gain), as well as a second group that are true losses. In general, the first group of "losses" merely serve to relocate the water to some other place from which it can be recovered. These "recoverable losses" are basically an economic or energy loss since the water is available when recovered. They are of appreciable magnitude and include seepage and runoff losses which respond to improved management and to improved technical and mechanical processes.

Seepage losses can be reduced: (1) By using the Irrigation Management Service

(Water and Power Resources Service) which determines when and how much to apply at an irrigation in order to reduce over-irrigation; (2) by improving application uniformity; (3) in conjunction with improved water scheduling; (4) by better understanding of the potential capabilities of the extensively used surface irrigation methods and management; (5) by correcting the conditions conducive to poor operations such as poor project schedules, nonuse of the Irrigation Management Service, inadequate designs, lack of irrigation reservoirs, or the equivalent flexible supply concept for surface irrigation systems; and (6) by such technical means as lining canals, and using pipelines and depressed canals.

Runoff losses occur because in order to assure never less than adequate water at the far end of a field more than enough water must be delivered. These losses can be reduced by: (1) Automation of canal systems; (2) incorporation of reregulating reservoirs with canals; (3) improved water schedules permitting variable flow rates and durations; and (4) installation of return flow systems for surface methods, especially in conjunction with irrigation reservoirs.

The second group of "losses," those which are difficult to reduce and recover, is true losses. These occur where: (1) Water salinity has become so concentrated that the water is practically unusable; (2) water evaporates directly from the soil surface, from reservoirs and canals, and from the drops in the air from sprinklers; (3) it percolates down so deep that it is essentially not recoverable or into ususually saline ground water; (4) it percolates into saline ground water; (5) it flows into oceans or salt lakes (recognizing the value of instream flow needs in estuaries or rivers above the point of entrance); and (6) it is used by noneconomic or undesirable vegetation (although this vegetation may have significant environmental and social value).

Demand Reduction through Technology

Municipal Use.—Landscape watering is the largest domestic use of water in many regions. Demand can be reduced when landscaping is done with native plants which live on natural supplies of water and are drought resistent. Following the 1976–1977 drought in California some water districts, e.g., North Marin, began working with nurseries and landscape architects to develop water-conserving landscaping plans. Such plans have been found to be both attractive and low in water use. Golf courses, parks, and green belts can conserve water by using reclaimed water.

The most common water conservation devices in residences are toilet dams, low flow shower heads and faucets, and water-conserving appliances. These devices are being installed in new construction in many regions of the country. Research is underway at the National Bureau of Standards, and in California to test the effectiveness of such devices. Retrofitting such devices in existing homes has relied on voluntary programs. Some utilities and government agencies have provided these devices at no cost with considerable success.

Industrial Use.—The Environmental Protection Agency has promulgated effluent standards for approx 2,000 industrial processes, the net effect of which has been to increase water costs and reduce use. The largest energy-related water use is for cooling electric generation plants. Effluent water temperature considerations for this industry are resulting in widespread installation of cooling towers. Withdrawals are consequently expected to diminish proportionately for

unit energy produced, although evaporation will increase. The effectiveness of conservation technology and the type of technology adopted will vary with industry and within industry with the process used.

Agricultural Use.—Technology which can be used to increase on-farm efficiency includes: lining of ditches and canals, selection of a proper irrigation method, automation of delivery systems to provide water as needed in frequency, rate, and duration, and system design to provide a greater capacity and degree of flexibility so that the farmer can optimize his needs and utilize the best methods. The automation and design of systems should consider variables such as soil type, crop varieties, stage of growth, and weather conditions. It is applicable to new systems and can often economically be applied to existing systems in which major rehabilitation is undertaken.

Agricultural irrigation methods may be broadly grouped into: (1) Above the ground—trickle, sprinkle; (2) on the ground (surface)—furrow, border-strip, basin; and (3) below the ground—sub and subsurface irrigation. Each method has its own potential for water conservation, but is limited by its range of application.

The above-ground methods are independent of topography and soil uniformity. They use moderate to high pressures requiring considerable energy. They also utilize special manufactured equipment of moderate to high cost. They need small, essentially continuous streams of water. The trickle method is almost always an automated operation, as are some sprinkler systems of a permanent type.

The surface methods are constrained by topography requiring gently sloping terrain to be economical otherwise land grading costs become excessive. They also need relatively uniform soils otherwise differential intake rates and available soil moisture capacity lead to difficult management problems or low efficiencies. To achieve low labor requirements, relatively large streams of water are desirable. The energy requirements are low, usually zero. Equipment is available to automate surface methods, but it has not become popular. The moving water surface methods—furrow and border-strips—almost always require some runoff at the lower end, the amount of which can be alleviated by good design and operation, and eliminated by use of a return flow system which makes reuse of the runoff practical. Where the runoff is recovered, the potential efficiency is the highest, otherwise it is only moderate. The basin method has a fairly high potential efficiency.

The below-ground methods—subirrigation which is done by raising and lowering the water table quickly, and subsurface irrigation which involves the use of tubing or devices below the surface—are very limited in their application.

Water Conservation and Law

Water and law are closely linked. Water use is a property right and is protected under the law. That is, the right of an irrigator or other user to use water is vested. In the west, where the major portion of irrigation water is used and where 90% of consumption is for irrigation, the doctrine of appropriation holds that water must be put to a beneficial use in order to obtain and retain the right to use the water. This "use it or lose it" emphasis does not always provide an incentive to conserve water. In some states, the irrigator who saves

water is entitled to the water saved; in other states the irrigator is not.

Agricultural Water.—In some instances, the right to use water is appurtenant to the land on which it is used. If reductions in diversions can be made while still maintaining the productivity of the land through more efficient water application, the user making the savings may not be able to claim the saved water. The water saved by reduced diversion would simply remain in the stream to support in-stream uses and be available for appropriation by junior appropriators and would be essentially the same as the water "wasted" by the first diverter since it returns to the stream. Thus, there would be little incentive for the existing user to undertake conservation measures. On the other hand, if the existing user can utilize the saved water in any beneficial manner including selling or trading it, as long as no injury occurred to other appropriators as a result, reduced use would be economically attractive.

Although studies have shown that it is possible to cut back significantly on use by reducing diversions to specific tracts of irrigated land while maintaining existing productivity, the amount of this water that may be put to a new beneficial use without interference with existing uses is much less. Specific information on the direct relationship between upstream diversions and use of the return flows downstream by other appropriators is often lacking. However, it is generally known that this use of return flow is very significant in most western river basins. The pattern of this return flow is important to the hydrologic and legal balance in a specific river basin. Excess irrigation water that percolates into the ground water may slowly return to the natural stream channel at a time later in the irrigation season when the streams would be otherwise dry and thus be available for appropriation by downstream users for their source of water during the later summer period. Often that pattern of flow may not be altered to the downstream user's detriment by upstream users.

Municipal Water.—Similar problems can accompany changes in purpose of uses, i.e., transfer of irrigation rights to a municipal and industrial use. In municipal systems problems associated with the appropriation doctrine are similar to those under irrigation. Municipal systems have less return flow on the surface or through the natural ground profile than irrigation. On the other hand, most of the domestic, commercial, and industrial use if returned to the municipal sewer systems, may be available for treatment and recycled to general or special uses such as park or golf course watering, thereby requiring less from the original source. Generally, a municipality may use and reuse its water as long as it is retained within its system. However, once it reaches a natural stream course, the city may lose its control and right. In certain circumstances, cities making major transbasin diversions of water (i.e., Denver, Colo.) are encouraged to use and reuse this imported water, whereas water originating within the basin may be used only once and is returned to the receiving stream after it has been used for diversion by downstream appropriators.

Water Conservation and Energy

Water conservation and energy also have important linkages. In fact, the energy-use implications of water conservation can be more significant than the amount of water saved. For example, in irrigation, energy consumption increases when changing from gravity to pressurized systems. Pumping from gound water

may require more energy than comparable surface water supplies. In multiple-purpose reservoirs, holding water back and saving it for future use may decrease hydroelectric power generation. Recycle systems at the end of irrigated fields will require pumping energy. Some new toilet devices require small motors to effect the flushing action using less water.

On the other hand, examples can be cited where using less water means using less energy. In any system requiring energy for water distribution or wastewater collection and treatment, energy reduction will be directly linked to reduction in pumping and processing energy requirements. Reductions in use of heated water have direct savings in energy costs. This can often be achieved by reducing the volume of water being pumped or processed, i.e., through water conservation. Explicit trade-offs between water and energy are difficult to make because the technological and social systems of which water and energy are a part are complex, and because, in the past, there has not been sufficient incentive to evaluate these trade-offs and thus we lack the desired knowledge of their interrelationship. In the future this is likely to change.

Conclusions

Water conservation is likely to play an important role in water resources planning in the future. From the preceding discussion on the different aspects of conservation, a number of guidelines can be formulated to assist in prudent conservation planning. These include:

1. Water is a renewable and reusable resource which varies with time, location, quantity, and quality. It may be used or lost depending upon local conditions.
2. Wise management of our water resources requires total water management, i.e., the conservation of supply and demand. Water conservation should be made part of this total water perspective.
3. Water conservation planning should be site specific. Programs should be tailored to the climate, type of use, and nature of supply and operation.
4. Affects of water conservation on the quantity and quality of surface and ground-water resources, on the interlinkage between water supply and wastewater systems and upon in-stream needs should be understood and assessed.
5. Conservation measures should be evaluated based upon their economic, social, and environmental benefits and costs, and upon their ability to achieve desired objectives.
6. Increases or decreases in energy consumption of conservation measures should be explicitly evaluated.
7. Water system reliability should be assessed and the system's capabilities understood. Design droughts should be made explicit and an emergency response plan required.
8. Reductions in assumed demand should also be made explicit and supported by continuing education.

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Samuel S. Baxter
James E. Crews
J. Ernest Flack
Bruce P. Glenn
John L. Merriam
George R. Oliger
Robert G. Potter
Kyle Schilling
William K. Johnson, Chairman

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CONVERSATIONAL WATER QUALITY DATA RETRIEVAL SYSTEM

By Douglas W. Larson[1] and Thomas Bingham[2]

INTRODUCTION

Water resource management often requires the use of a computer to store and manipulate large quantities of data. But data retrieval may present a problem for the investigator or program manager who is inexperienced with computers, terminal communications and commands, and syntax language, or who accesses the stored data so infrequently that each new retrieval session requires, essentially, a costly and perhaps time-consuming "re-learning" of procedures and language. Ideally, the most efficient, useful retrieval system would probably be one requiring the fewest commands in the simplest language. Here we describe a data management system which can be activated and used quickly, with minimal training, jargon, and incentive, while still employing the latest data retrieval software available.

SYSTEM DESCRIPTION

Since 1974, we have collected much physical, chemical, and biological data for reservoirs and rivers in western Oregon. This information is handled through use of the data-base management system SIR (scientific information retrieval) (3), and a FORTRAN program which interfaces SIR with the user. SIR was chosen for several reasons:

[1]Limnologist, Hydr. Section, United States Army Corps of Engrs. Dist., Portland, Ore. 97208.
[2]Statistician, Boeing Computer Service, Energy-Tech.-Application Div., Tukwila, Wash. 98188.

Note.—Discussion open until August 1, 1981. To extend the closing date one month, a written request must be filed with the Manager of Technical and Professional Publications, ASCE. Manuscript was submitted for review for possible publication on February 19, 1980. This paper is part of the Journal of the Water Resources Planning and Management Division, Proceedings of the American Society of Civil Engineers, ©ASCE, Vol. 107, No. WR1, March, 1981. ISSN 0145-0743/81/0001-0239/$01.00.

1. SIR is a hierarchical system with the capability to pinpoint sub-populations of data, and then process only those portions of the data base at a relatively low cost.
2. SIR has a versatile reporting capability which can produce reports under any format of the user's choice.
3. SIR has a built-in direct link with two major statistical packages designated as the statistical package for social sciences (SPSS) (2) and the biomedical computer programs P-Series (1) via system file creation, which facilitates easy, yet powerful statistical analyses.

The FORTRAN interface program was designed to prompt the user with questions, the answers to which describe the exact nature of the retrieval. SIR

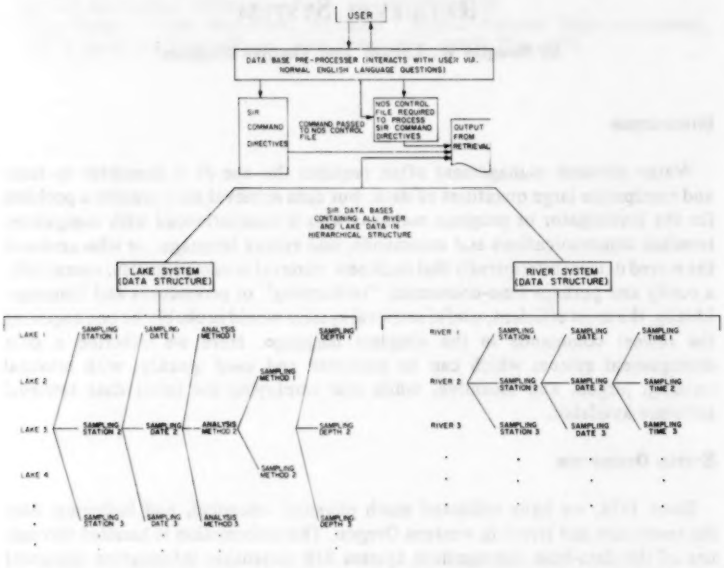

FIG. 1.—Schematic of Water Quality Data Retrieval System (NOS = Network Operating System)

directives, corresponding to the answers as created by the FORTRAN program, are then executed. The results of the retrieval are displayed to the user in the form of the user's choice (see Fig. 1).

For users who might be unfamiliar with the interface program, a self-documenting capability was built into the program so that it could be operated successfully with no user's manual. Essentially, this documentation consists of several "menus" which are displayed individually upon request, thereby giving all available responses to questions about a particular category of information.

Overall, the system combines a tutorial interactive capability with batch

TABLE 1.—Example of Typical Data Retrieval Session Using Conversational Water Quality Data Management System

C >	CALL, RETRIEV
	please enter your name:
I >	SMITH
	enter subject category (0 = menu):
I >	0
	enter one of the following numeric codes:[a]
	1. river data
	2. lake data
	3. groundwater
I >	2
	enter any assortment of record types desired[a] (0 = menu):
I >	0
	1. nutrients
	2. pesticides
	3. biological
I >	1 3
	enter the numeric codes representing the desired parameters to be retrieved from record type 1[a] (0 = menu):
I >	0
	1. nitrate-nitrogen
	2. orthophosphate
	3. silica
I >	1 2
	enter the numeric codes representing the desired parameters to be retrieved from record type 3[a] (0 = menu):
I >	0
	1. phytoplankton primary production
	2. phytoplankton chlorophyll concentrations
	3. phytoplankton species composition
I >	2 3
	enter the river/lake basin number[a] (0 = menu):
I >	0
	1. Columbia
	2. Willamette
	3. Rogue
I >	2
	enter the numeric codes representing the desired lakes to be retrieved from record type 2[a] (0 = menu):
I >	0
	1. Lookout Point
	2. Hills Creek
	3. Cougar
I >	2
	enter the desired station numbers[a] (0 = menu):
I >	0
	1. HC5
	2. HC12
	3. HC26
I >	HC5 HC26

TABLE 1.—*Continued*

	enter the date from which the retrieval is to begin. The required format is DD MM YY:
I >	15 5 75
	enter the date on which the retrieval is to end. The required format is DD MM YY:
I >	30 8 78
	enter output options[a] (0 = menu):
I >	0
	1. create easy-graph files for plotting 2. re-sort data records by one or more parameters 3. create SIR line printer plots of any number of parameter pairs 4. create an SPSS system file for statistical analyses 5. print-out requested data
I >	5
	enter your desired job priority[a] (0 = menu):
I >	0
	1. standby 2. four hours turn around 3. one hour turn around
I >	3
	successful completion of water quality information system[b]

[a] An unlimited number of numeric codes, record types, or options can be listed; examples are given.

[b] The system is not restricted to water quality data; application is intended for other types of data bases.

processing which may contribute to greater flexibility, responsiveness, and ease in data retrieval, and yet be relatively inexpensive and require shorter periods of time at the terminal because of the batch job feature. This differs from systems which exclusively use batch processing to retrieve data—e.g., STORET (4) or WATSTORE (5)—or are purely interactive.

System Operation

To operate our system, the user first logs on by dialing, in our case, Boeing EKS (Enhanced Kronos System) and providing a user identification code. Completion of log-on is signified by a "C" prompt, i.e., C >. The user then executes system by entering the command "CALL, RETRIEV." From this point on, the system questions the user in "everyday" conversational language concerning information needed to perform the retrieval. If the user is unsure as to how to initiate a response (e.g., to answer a specific question posed by the system), a "menu" of available responses may be activated by entering a "key" number (usually zero) which is also indicated by the system (see Table 1).

If the user enters an invalid response, a "diagnostic" is printed by the program with the request to try again. Thus, "bug-free" SIR directives are always written, thereby freeing the user of the problem of using the "debugging" code. At any point during execution, the entire run may be aborted by entering "STOP."

Re-execution is done by reentering "CALL, RETRIEV." After completing all desired retrievals in a given session, the user can log off by entering "BYE" and then hanging up the phone.

Because all operating commands are built into the system, little or no experience with any form of computing is required to operate the system other than the procedure given in Table 1. Any files that are to be saved by the system for subsequent statistical analyses (e.g., by SPSS) can be stored under the names chosen by the user during the execution of the system. The use of these files, however, will require some knowledge of SPSS and computer operating language. Requested data can be printed automatically on a local line printer.

Our system is currently limited to Boeing EKS (i.e., the system is not designed to interface with other data management systems), although the data base could be transferred en masse to STORET (4) or WATSTORE (5), for example.

Summary and Conclusions

A system is described which simplifies the process of retrieving data from computer storage. "Everyday" conversational language forms the basis of communication between data retriever and computer, thereby minimizing the need for specialized training and knowledge in computer operations.

The system allows for relatively easy access to stored data of any kind, and can rapidly generate data tabulations, graphics, and statistical plots and analyses for prompt assessment of water quality or for use in continued aquatic research.

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REDUCING HYDROLOGIC PARAMETER UNCERTAINTY

Yeou-Koung Tung[1] and Larry W. Mays,[2] A. M. ASCE

INTRODUCTION

In water resources engineering project design, hydrologic frequency analysis plays an important role. It is always desirable, if somewhat idealistic to expect, to have procedures for accurate prediction of hydrologic quantities, e.g., flood magnitudes and rainfall depths. This could be achieved if a large number of hydrologic data were available for the site under investigation. However, hydrologic data available for frequency analysis commonly extend over a period of only 10 yr–30 yr, with some locations having longer records and a large number of locations having no records. Stream flow and rainfall processes are often (usually) assumed to be stochastic processes because of the natural, or inherent, randomness of their occurrence. Because we lack perfect information about these processes, i.e., infinitely long historical records, there exist informational uncertainties about the processes which are parameter and model uncertainties. There is currently much debate among hydrologic researchers concerning these uncertainties and how to consider them. The writers recognize the importance of both these uncertainties; however, methods for reducing only parameter uncertainty are considered in this paper.

The common practice in hydrologic frequency analysis is to fit observations to theoretical probability distributions. The practical problems that are encountered are: (1) The choice of a distribution; and (2) an estimation technique for the parameters of the distribution. The parameters are commonly derived by the method of moments but can also be derived by the method of maximum likelihood. Because only a limited number of hydrologic data are usually available, sample sizes are normally too small to permit accurate estimation of statistical

[1]Research Asst., Dept. of Civ. Engrg., Univ. of Texas, Austin, Tex. 78712.
[2]Asst. Prof., Dept. of Civ. Engrg., Univ. of Texas, Austin, Tex. 78712.

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parameters, mean, standard deviation, and skewness. Consequently, the parameters should be considered as random variables and subject to sampling errors. A procedure would be desirable that can be used to modify parameter estimates to reduce the errors.

It is only recently that other uncertainties, in addition to the natural or inherent hydrologic uncertainties, have been considered explicitly on a scientific basis. Basically there have been works to consider the hydrologic uncertainties (inherent, parameter, and model) and also a few attempts to look at the hydraulic uncertainties. Most of the work reported in the literature to consider the hydrologic uncertainties has been through a Bayesian framework. Some works have considered the natural and parameter uncertainties or the natural and model uncertainties, and some works have attempted to consider all three uncertainties. Most of these works have dealt with improving flood frequency estimates by incorporating parameter or model uncertainties into the hydrologic analysis, or both (4,6,7,10,11,22,24,25,26).

The objective of this paper is to introduce a methodology that can be used in hydrologic frequency analysis to reduce the parameter uncertainty. The methodology consists of developing generalized values of the parameters (mean, standard deviation, and skewness) through the use of a weighting procedure between sample and regionalized statistics. The weights are defined as a function of the variances of the sample parameters and regionalized parameter values. The variances of the sample parameters are determined using two nonparametric statistical methods, i.e., the jackknife method and the bootstrap method. The variances of the regionalized parameters are determined through regression analysis. The methodology can be applied to any probability distribution for frequency analysis; however, for the sake of illustration only flood flow frequency analysis using the log-Pearson Type III distribution is considered. The ability of this methodology is illustrated with flood flow frequency data for the Southwestern United States. Comparisons are also made of different weighting methods for defining the weighting factor between the regional and sample skewness based upon their capability for predicting flood events.

Flood Frequency Analysis: Water Resources Council (WRC) Method

The United States Water Resources Council (1967) recommended using the log-Pearson Type III distribution as a standard model for flood flow frequency studies. This was an attempt to promote a uniform and consistent approach to flood-flow determination for use in all Federal planning involving water and related land resources. The Council also recommended its use by all state and local government and private engineers. The log-Pearson Type III was chosen because it provided a relatively good fit in a number of cases to observed data over a range of statistics. Bobée (5) showed that this distribution has some questionable properties for some combinations of estimated parameters. Matalas, et al. (17) have demonstrated the inability of this distribution to represent many flood data.

The log-Pearson Type III distribution is a three-parameter distribution requiring the mean, $\bar{Y}_s$, the variance S_s^2, and the coefficient of skewness, G_s, which can be estimated from the sample data by the method of moments using

$$\bar{Y}_s = \frac{1}{N}\sum_{i=1}^{N} y_i \quad \ldots\ldots (1)$$

$$S_s^2 = \frac{1}{N-1}\sum_{i=1}^{N} (y_i - \bar{Y}_s)^2 \quad \ldots\ldots (2)$$

$$G_s = \frac{N}{(N-1)(N-2)S_s^2}\sum_{i=1}^{N} (y_i - \bar{Y}_s)^3 \quad \ldots\ldots (3)$$

in which y_i = the log transformation of the flood magnitude; N = the number of observations; and subscript s signifies that the parameter is estimated from the sample data.

The Water Resources Council (WRC) recognized that the skewness has greater sensitivity to the behavior of data than does the mean and standard deviation, suggesting the use of generalized skew coefficients based upon sample estimates and regional estimates. Because the estimate of skewness is biased and subject to large sampling errors, Hardison (1974) developed generalized skew coefficients for use in determining flood-flow frequency curves that follow the log-Pearson Type III distribution. These generalized skew coefficients were illustrated by isopleths on a map of the United States. The Hydrology Committee of the WRC also suggested the use of a regional skew map to obtain a generalized skew coefficient for a specific site. Furthermore, a weighting procedure was proposed to combine the skewness derived from the sample, G_s, and the map skewness, G_r, to derive a weighted skew, $\hat{G}$, as follows:

$$\hat{G} = W_G [G_s + (1 - W_G)]\, G_r \quad \ldots\ldots (4)$$

in which W_G = a weighting factor, $0 \leq W_G \leq 1$.

The weight, W_G, for skewness was first introduced by WRC (21) as

$$W_G = 0,\ N < 25; \quad W_G = \frac{N-25}{75},\ 25 \leq N \leq 100;$$

$$W_G = 1,\ N > 100 \quad \ldots\ldots (5)$$

The WRC suggests the use of sample statistic $\bar{Y}_s$ and S_s along with weighted skewness in the flood-frequency analysis. This method has no theoretical basis and determines the weight regardless of sample and regional information available. It has the disadvantage of discarding information contained in the sample collection when the size is less than 25 while taking full confidence on the sample skewness when sample size is greater than 100 neglecting the fact that the sample statistic is a random variable with associated variance even though it is derived from a large sample.

Tasker (19) used the results obtained by Wallis, et al. (23) and proposed the weighting factor for skewness as

$$W_G = \frac{N}{N+20} \quad \ldots\ldots (6)$$

which is also a function of only the sample size.

Weighted Parameter Estimates

Weighted parameter estimates are now considered that combine both parameter estimates from sample data and estimates from regional information. Hydrologists have recognized that certain hydrologic information can be transferred among river basins. The transferring of information has the function of data augmentation which hopefully increases the reliability of the analysis. A general equation relating parameter estimates based upon the sample data and upon regional information can be expressed as

$$\hat{\theta} = W_\theta [\theta_s + (1 - W_\theta)] \theta_r \quad \ldots \ldots \ldots

this problem. These nonparametric methods do pay a computational price for their freedom from normal distribution theory. However, the use of the computer makes these methods very tractable rather than a nightmare for the user. Since both the mean and standard deviation are two parameters also involved, in addition to the skewness in flood flow frequency analysis, they can all three be treated in a similar manner. In other words, variances of the mean, standard deviation, and the skewness of the sample data can be computed by applying the jackknife and bootstrap methods to the sample data, and then used to determine the weights.

Variance of Sample Estimators by Jackknife

The jackknife, introduced in late 1950, is an intriguing attempt to answer an important statistical problem, i.e., having computed an estimate of some quantity of interest, what accuracy can be attached to the estimate? Miller (18) gave an excellent review of this method. The jackknife method has the function of bias correction which makes this method more favorable. The most commonly used expression for the "accuracy" of an estimate is the standard deviation. The jackknife procedure can be used to compute the standard deviation of parameter estimates as follows:

1. Compute the estimate of interest, θ_s, from the N sample observations.
2. For each observation $i = 1, \ldots, N$, compute $\theta_s^{(i)}$ from $N - 1$ observations with the ith observation deleted from the data set.
3. Compute the accuracy of θ_s using

$$\hat{\sigma}^{(J)} = \left[\frac{N-1}{N}\sum_{i=1}^{N}(\theta_s^{(i)} - \theta_s)^2\right]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

in which $\hat{\sigma}^{(J)}$ = the jackknifed standard deviation of the estimate θ_s. For the purpose of bias correction, statisticians usually replace θ_s by $1/N\ \Sigma_{i=1}^{N}\ \theta_s^{(i)}$ in Eq. 11; otherwise, with no bias correction, θ_s is used.

Therefore, for a given set of observations the jackknifed standard deviation of the estimate, θ_s, can be computed by the procedures previously described. The variance of θ_s is expressed as

$$\text{Var}\,(\theta_s) = [\hat{\theta}^{(J)}]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

which can be used to calculate the weight using Eq. 7. Readers are referred to Efron (14) and Miller (18) for the details of the theory of this method.

Variance of Sample Estimators by Bootstrap

Efron (13) developed the bootstrap method which can also be used to access the accuracy of any estimate of interest derived from a sample. From the theoretical point of view, the bootstrap is more widely applicable than the jackknife, and also more dependable (13,14). The procedures of this method are outlined as follows (13):

1. Let $\hat{F}$ be an empirical distribution of N observed data points, $\{y_i, i =$

1, ..., N}, i.e., $1/N$ is the probability of occurrance assigned to each of the observations.

2. Use a random number generator to draw N new points $\{y_i^*, i = 1, ..., N\}$ independently and with replacement from $\hat{F}$, so each new point is an independent random selection of one of the N original data points. This set of N new points is called the bootstrap sample which is a subset of the original data points.

3. Compute the estimate θ_s for the bootstrap sample $\{y_i^*, i = 1, ..., N\}$.

4. Repeat steps 2 and 3 a large number of times, say $m = 1, ..., M$ times each time using an independent set of new random numbers to generate the new bootstrap sample. The resulting sequence of bootstrap statistics are $\theta_s^{*(m)}$, $m = 1, ..., M$.

5. The variance of θ_s can be calculated as

$$\text{Var}(\theta_s) = \frac{1}{M}\sum_{m=1}^{M}(\theta_s^{*(m)} - \bar{\theta}_s^*)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

in which $\bar{\theta}_s^* = (1/M)\sum_{m=1}^{M}\theta_s^{*(m)}$.

The jackknife and bootstrap methods previously described can be used to compute the variance of any number of statistics, e.g., mean, standard deviation, and skewness, derived from the sample. The other information required for computing the weight is the variance of the parameter derived from the regional basis. As previously mentioned, the variance of regional parameters, θ_r, can be computed using regression equations.

Variance of Regional Parameters

The variance of regional estimators can be obtained by regression analysis which relates the regional estimators to physiographic or meterological variables, or both. The applications of regression analysis are very fruitful and extensive by hydrologists. However, there has not been an equivalent amount of effort in understanding all the effect of assumptions that the regression theory has on the regression models by the hydrologists. Among regression models the linear model is the most popular one used which has the general form

$$Y_j = \beta_o + \beta_1 X_1 + \ldots + \beta_k X_k + \epsilon_j, \quad j = 1, ..., n \quad \ldots\ldots\ldots\ldots\ldots \quad (14)$$

or in the matrix notation:

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

in which $\mathbf{Y}$ = an $(n \times 1)$ vector of dependent variables (or responses); $\mathbf{X}$ = an $(n \times k)$ matrix of k independent variables; $\boldsymbol{\beta}$ = a $(k \times 1)$ vector of unknown regression parameters; and $\boldsymbol{\epsilon}$ = an $(n \times 1)$ vector of random errors.

The method often employed for equation fitting is that of least squares, having the following assumptions:

1. The form of the model is correct.
2. The responses $\mathbf{Y}$ are statistically independent.
3. The conditional mean of the random response vector $\mathbf{Y}$ for a given $\mathbf{X}$ is $E(\mathbf{Y}|\mathbf{X}) = \mathbf{X}\boldsymbol{\beta}$, in which $E(\mathbf{Y}|\mathbf{X})$ is the expected value.

4. Constant variance, i.e., Var $(\mathbf{Y}|\mathbf{X}) = \sigma^2\mathbf{Y}$, in which $\mathbf{I}$ is an $(n \times n)$ identity matrix.

5. The distribution of $\mathbf{Y}$ is multinormal with mean $\mathbf{X}\boldsymbol{\beta}$ and covariance matrix $\sigma^2\mathbf{I}$.

Assumption four is not necessary in the least squares method. If assumption four does not hold, the weighted least squares (WLS) or a transformation of dependent variables, which stabilizes the variance, can be applied. In most hydrologic applications this assumption is implicitly taken and the ordinary least squares method (OLS) is applied. Assumption five is required which validates the statistical inference of the regression parameters estimated. The variance of $\mathbf{Y}$ given $\mathbf{X}$ in the OLS method σ^2 can be estimated by

$$\hat{\sigma}^2 = \frac{\mathbf{e}^T\mathbf{e}}{(n-k)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

in which $\mathbf{e} = \mathbf{Y} - \mathbf{X}\hat{\boldsymbol{\beta}}$; $\mathbf{e}^T$ = the transpose of $\mathbf{e}$; and $\hat{\boldsymbol{\beta}} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}\mathbf{Y}$, which is the OLS estimator of the regression parameter, $\boldsymbol{\beta}$, in the model.

It is always necessary to examine the validity of the aforementioned assumptions after the regression analysis is made, which can be done by the analysis of residuals. The most commonly used method is to analyze the scatter plots. Excellent analyses of residuals are given by Anscombe and Tukey (1). Draper and Smith (12) and Daniel and Wood (9) provide good illustrations on this topic. In general, the analysis of residuals helps the analyst to test the validity of his model and to provide the necessary information for modifying the model. It always pays to identify the influential observations which affect the results of analysis a great deal. Cook (8) developed a statistic, D_i, named Cook's distance, which measures the overall impact of any single data point on the least squares solution, as

$$D_i = \frac{(\hat{\boldsymbol{\beta}}_{(i)} - \hat{\boldsymbol{\beta}})^T\mathbf{X}^T\mathbf{X}(\hat{\boldsymbol{\beta}}_{(i)} - \hat{\boldsymbol{\beta}})}{k\hat{\sigma}^2}, \quad i = 1, \ldots, n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

in which D_i = a measure of the distance between $\hat{\boldsymbol{\beta}}$ and $\hat{\boldsymbol{\beta}}_{(i)}$, where $\hat{\boldsymbol{\beta}}_{(i)}$ = the OLS estimator of $\boldsymbol{\beta}$ with the ith observation deleted.

Furthermore, D_i can be expressed as

$$D_i = \left[\frac{Y_i - \mathbf{x}_i^T\hat{\boldsymbol{\beta}}}{\hat{\sigma}\sqrt{1-\mathbf{v}_i}}\right]^2\left[\frac{\mathbf{v}_i}{1-\mathbf{v}_i}\right], \quad i = 1, \ldots, n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

in which $\mathbf{x}_i$ = the vector of the ith independent variables; and $\mathbf{v}_i = \mathbf{x}_i^T(\mathbf{X}^T\mathbf{X})^{-1}\mathbf{x}_i$.

The first term on the right of Eq. 18 is the square of the studentized residual while the second term is the moment arm. It has been shown by Cook (8) that D_i is approximated by an F distribution with k and $(n-k)$ degrees of freedom. A standard hypothesis test can then be applied to assess the influence of data points on the regression estimation. Maximum values of the coefficient of determination (r^2) was not the only criterion used to select the best subset of independent variables in the regression model as the value of r^2 can always be increased by adding more terms to the model. An adjusted square of the

multiple correlation coefficient can be used as

$$\bar{r}^2 = r^2 - \frac{k-1}{n-1}(1-r^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

The $\bar{r}^2$ will increase only when the t statistic of added regression coefficients are larger than unity. Other criteria such as the residual standard error, $\hat{\sigma}$, and Mallows' C_p statistics (16) which measure the sum of squared bias plus the squared random error in Y at all data points, are used. Mallows C_p statistic is defined as

$$C_p = \frac{RSS_p}{\hat{\sigma}^2} - (n-2p) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

in which RSS_p = residual sum of square of regression model with p unknown coefficients to be estimated. The Mallows C_p statistic provides a measure of the mean square error of the predicted value for a p parameter regression model.

Regression Analysis Study for Southwest Region

To reduce parameter uncertainty by using the weighting procedure mentioned requires the knowledge of information contained in both sources, i.e., the regional and local sample data, which is expressed as the variance of the estimate. For the sake of illustration of the procedure, the log-Pearson Type III distribution is considered for the frequency analysis of flood magnitude. Equations 1–3 were used to compute the values of parameters, mean, standard deviation, and skewness of log-transformed stream flow observations from the sample. The variance of these parameter estimates derived from the sample was determined by the method of jackknife and bootstrap.

The values of the parameters and their respective variances for the region were determined by regression analysis. Benson (3) applied regression analysis to the Southwestern region of the United States relating the flood magnitudes of specified return periods to meterological and physiographical characteristics of the river basins. He divided the region into two subregions based on the mechanism as to how the floods are generated, i.e., floods produced by snowmelt and local thunderstorms or widespread tropical storms. The data used herein involved the subregion where floods are produced by thunderstorms which includes the central and eastern part of Texas and a small part of western Louisiana. The ordinary least squares method was applied to relate the regional parameters, the mean ($\bar{Y}_r$), the standard deviation (S_r), and the skewness (G_r), to the physiographic and meterologic characteristics, e.g., the contributing drainage area (A) in square miles, the main channel slope (S_t) (85%–10% points) in feet per mile, the percentage of surface storage (S_r), the total main channel length (L) in miles, the 10-yr 24-h rainfall intensity (I) in inches, the mean annual number of thunderstorm days (N_t), and the ratio of runoff to precipitation during the month when the annual maximum peak discharge occured (R). A total of 95 gaging stations were analyzed in this region. The procedure for examining the validity of assumptions in the OLS method consisted of an analysis of the residuals and of Cook's distance. The resulting regression equations for the regional parameters used in log-Pearson Type III distribution were as follows:

$$\ln \bar{Y}_r = 1.424 + 0.064 \ln (A) + 0.0083(S_l) - 0.064 \ln (S_t) + 0.091 \ln (N_t) + 0.057 \ln (R) \quad (21)$$

$$\ln (S_r) = 3.24 + 0.178 \ln (A) - 0.263 \ln (S_t) - 0.414 \ln (L) + 0.411 \ln (I) - 0.894 \ln (N_t) - 0.065 \ln (R) \quad (22)$$

and $$G_r = -3.601 + 0.102 \ln (A) - 2.564 \ln (S_t) + 4.201 (\ln (S_t))^2 + 0.724 \ln (N_t) \quad (23)$$

Table 1 presents r^2, $\bar{r}^2$, $\hat{\sigma}$, and C_p for the regression equations. The variances of $\bar{Y}_r$, S_r, and G_r were needed for computing the weights W_θ for each parameter θ by Eq. 7. The square of the standard error of residual, Eq. 16, provided by regression analysis could not be used directly as the regional variance for $\bar{Y}_r$ and S_r in this study. By analysis of residuals for Eqs. 21 and 22, the normality assumptions hold; therefore, $\bar{Y}_r$ and S_r are log-normally distributed so that the variances of $\bar{Y}_r$ and S_r can be computed using

$$\text{Var}(\ ) = U^2(e^{\hat{\sigma}_1^2} - 1) \quad (24)$$

in which Var = the variance of $\bar{Y}_r$ or S_r; and $\hat{\sigma}_1$ = the standard error of

TABLE 1.—Statistics Used for Selecting Variables in Regression Analysis

Equation (1)	r^2 (2)	$\bar{r}^2$ (3)	C_p (4)	$\hat{\sigma}$ (5)
21	0.6667	0.6488	4.7	0.04817
22	0.6244	0.6002	6.2	0.2131
23	0.1637	0.1281	1.3	0.5080

residual of $\ln (\bar{Y}_r)$ or $\ln (S_r)$. In addition, U = the mean of $\bar{Y}_r$ or S_r for a given **X**, expressed as

$$U = \exp\left(\frac{U' + \hat{\sigma}_1^2}{2}\right) \quad (25)$$

in which U' = the value of $\ln (\bar{Y}_r)$ or $\ln (S_r)$ provided by Eq. 21 or 22. Because of the log-transformation of the regression (Eqs. 21 and 22), the variance of $\bar{Y}_r$ and S_r are data dependent while that of G_r is constant, in this study 0.508^2. For example, the variance of $\bar{Y}_r$ is computed using

$$\text{Var}(\bar{Y}_r) = U_1^2\{\exp[\text{Var}(\ln(\bar{Y}_r)) - 1]\} \quad (26)$$

in which $$U_1 = \exp\left(\ln \bar{Y}_r + \frac{\text{Var}[\ln(\bar{Y}_r)]}{2}\right) \quad (27)$$

Summary of Methods Tested

The following is a summary of parameter estimation methods considered:

1. Sample statistics.—Use Eqs. 1, 2, and 3 to compute parameters, i.e., the

mean, standard deviation, and skew, respectively.

2. WRC Method.—This method uses Eqs. 1 and 2 to compute the mean and standard deviation and Eq. 4 to compute a generalized skew in which G_s is from Eq. 3; G_r is a map skew from Bulletin 17; and the weight, W_G, is from Eq. 5.

3. Taskers Method.—This method used Eqs. 1 and 2 to compute the mean and standard deviation and Eq. 4 to compute a generalized skew in which G_s is from Eq. 3; G_r is a map skew from Bulletin 17; and the weight, W_G, is from Eq. 6.

4. Fishers Method.—This method used Eqs. 1 and 2 to compute the mean and standard deviation and Eq. 4 to compute a generalized skew in which G_s is from Eq. 3; G_r is a map skew from Bulletin 17; and the weight is computed using Eq. 9 where $\theta = G$. The Var $(G_r) = 0.55^2$ from Bulletin 17 and Var (G_s) is found using Eq. 10.

5. Tung and Mays Method J.—Computes a generalized mean, $\hat{Y}$, using Eq. (7), i.e.:

$$\hat{Y} = W_{\bar{y}}[\bar{Y}_s + (1 - W_{\bar{y}})]\ \bar{Y}_r \quad \ldots \quad (26)$$

in which $\bar{Y}_s$ is computed using Eq. 1; $\bar{Y}_r$ is computed using Eq. 21; and $W_{\bar{y}}$ is computed using Eq. 9 or

$$W_{\bar{y}} = \frac{\text{Var}\,(\bar{Y}_r)}{\text{Var}\,(\bar{Y}_s) + \text{Var}\,(\bar{Y}_r)} \quad \ldots \quad (27)$$

The Var $(\bar{Y}_r)$ is computed using Eqs. 26 and 27 and Var $(\bar{Y}_s)$ is computed using the jackknife method (Eqs. 11 and 12). A generalized standard deviation, $\hat{S}$, is computed using Eq. 7, i.e.:

$$\hat{S} = W_s[S_s + (1 - W_s)]\ S_r \quad \ldots \quad (28)$$

in which S_s is computed using Eq. 2; S_r is computed using Eq. 22, and W_s is computed using Eq. 9 or

$$W_s = \frac{\text{Var}\,(S_r)}{\text{Var}\,(S_s) + \text{Var}\,(S_r)} \quad \ldots \quad (29)$$

The Var (S_r) is computed using Eqs. 24 and 25, and Var (S_s) is computed using the jackknife method (Eqs. 11 and 12).

A generalized skew $\hat{G}$ is computed using Eq. 7 the form of which is Eq. 4 in which G_s is computed using Eq. 3; G_r is computed using Eq. 23; and W_G is computed using Eq. 9 or

$$W_G = \frac{\text{Var}\,(G_r)}{\text{Var}\,(G_s) + \text{Var}\,(G_r)} \quad \ldots \quad (30)$$

The Var (G_r) is 0.508^2 as stated previously, and Var (G_s) is computed using the jackknife method (Eqs. 11 and 12).

6. Tung and Mays Method B.—This method is identical to the Tung and Mays Method J except here the Var $(\bar{Y}_s)$, Var (S_s), and the Var (G_s) are computed using the bootstrap (Eq. 13).

Application

In this section the application of the parameter uncertainty reducing procedure and the comparison of its capability in flood prediction are made considering different weighting procedures. Five drainage basins in the region are considered. The United States Geological Survey USGS gaging station number, length of record, and values of their physiographical and meterological variables are tabulated in Table 2.

Six different procedures, i.e., the method of using sample statistics only, the WRC method, Taskers method, Fishers method, Tung and Mays Method J (TMJ), and Tung and Mays Method B (TMB) were first tested for their capability of flood prediction with the consideration of the uncertainty due only to skewness. The test procedure was:

1. Use the first chronological $N_p = 10$ observations of the total N observations to perform a flood frequency analysis by using the six different methods previously mentioned for parameter estimation. The analytical method of curve fitting computes (estimates) flood magnitudes, $\hat{Z}_T$, for various return periods, T, for the methods of sample statistics, WRC, Tasker and Fisher, using

$$\log(\hat{Z}_T) = \bar{Y}_s + K_T S_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (31)$$

in which $\bar{Y}$ = the mean of the log-transformed N_p observations; S = the standard deviation of the log-transformed N_p observations; and K_T = the frequency factor which is a function of the skewness and the probability of exceedance, $1/T$.

For the TMJ and TMB methods the frequency equation is

$$\log(\hat{Z}_T) = \hat{Y} + K_T(\hat{S}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (32)$$

in which K_T = a function of the return period and generalized skew.

2. Calculate ERR_1 for each method

$$\mathrm{ERR}_1 = \left[\sum_{t=1}^{N}\left(\frac{Z_{T(t)} - \hat{Z}_{T(t)}}{\hat{Z}_{T(t)}}\right)^2\left(\frac{1}{N}\right)\right]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (33)$$

in which N = total number of observations at the gaging station tested; $Z_{T(t)}$ = the N observed flood magnitudes with return period of $T(t) = (N + 1)/t$; and $\hat{Z}_{T(t)}$ = the estimate of the flood magnitude with the same return period determined from the frequency (Eq. 31) based upon the N_p observations. The reason for choosing such a criterion as Eq. 33 is that it reveals the average

TABLE 2.—Basin Characteristics for Gaging Stations

Station (1)	N (2)	A (3)	S_l (4)	S_s (5)	L (6)	I (7)	N_s (8)	R (9)
8022500	64	4,839	1.25	1.27	235	6.33	49	0.62
8030500	66	9,329	0.96	1.18	427	6.78	57	0.63
8033500	75	3,637	1.29	1.13	253	6.61	52	0.63
8057000	73	6,106	3.67	1.72	188	5.68	47	0.40
8096500	79	20,007	2.77	1.23	706	5.14	43	0.38

TABLE 3.—ERR_1 and ERR_2

Method (1)	N_p = 10 ERR_1 (2)	10 ERR_2 (3)	20 ERR_1 (4)	20 ERR_2 (5)	40 ERR_1 (6)	40 ERR_2 (7)
(*a*) Station 8022500						
Sample	0.454	9,270	0.172	4,040	0.138	4,580
WRC	0.445	10,500	0.177	4,490	0.139	4,600
Tasker	0.441	10,100	0.171	4,420	0.138	4,590
Fisher	0.441	9,970	0.171	4,390	0.138	4,590
Tung and Mays Method J	0.289	6,930	0.130	3,200	0.123	3,880
Tung and Mays Method B	0.305	7,200	0.126	3,110	0.124	3,900
(*b*) Station 8030500						
Sample	0.327	9,130	0.156	6,130	0.0767	3,260
WRC	0.342	7,410	0.165	7,410	0.0820	3,620
Tasker	0.330	7,160	0.158	6,630	0.0788	3,400
Fisher	0.329	7,200	0.157	6,590	0.0787	3,390
Tung and Mays Method J	0.278	6,190	0.156	5,070	0.0758	3,180
Tung and Mays Method B	0.279	6,640	0.154	5,010	0.0750	3,150
(*c*) Station 8033500						
Sample	0.188	4,000	0.0325	797	0.0941	2,180
WRC	0.104	2,300	0.0408	992	0.0987	2,270
Tasker	0.126	2,800	0.0365	892	0.0960	2,220
Fisher	0.131	2,930	0.0362	885	0.0959	2,210
Tung and Mays Method J	0.0876	2,040	0.0351	857	0.0863	2,010
Tung and Mays Method B	0.0958	2,210	0.0389	948	0.0965	2,230
(*d*) Station 8057000						
Sample	0.983	36,400	0.207	13,700	0.0940	5,800
WRC	0.911	13,300	0.287	5,390	0.1200	5,470
Tasker	0.824	10,700	0.232	7,980	0.0926	4,510
Fisher	0.824	15,800	0.229	4,670	0.0907	4,290
Tung and Mays Method J	0.521	15,800	0.156	4,670	0.0907	4,290
Tung and Mays Method B	0.560	13,600	0.160	5,260	0.0915	4,390
(*e*) Station 8096500						
Sample	0.176	14,400	0.0847	15,400	0.177	13,000
WRC	0.171	15,300	0.0987	6,780	0.182	11,300
Tasker	0.172	14,900	0.0823	9,690	0.179	11,900
Fisher	0.172	14,900	0.0818	10,000	0.179	12,000

TABLE 3.—*Continued*

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Tung and Mays Method J	0.119	7,950	0.0600	6,300	0.166	10,600
Tung and Mays Method B	0.120	8,160	0.0606	7,050	0.166	11,000

value of the ratio to which the actual observations deviate from the predicted values.

3. Calculate ERR_2 for each method.

$$ERR_2 = \left[\sum_{i=1}^{N} (Z_{T(i)} - \hat{Z}_{T(i)})^2 \left(\frac{1}{N}\right)\right]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (34)$$

4. Repeat steps 1 and 2 using $N_p = 20$, then $N_p = 40$.

The foregoing testing procedure was performed for each of the five gaging stations tabulated and the values of the error criteria ERR_1 and ERR_2 were determined for each method and different sample sizes. The number of bootstrap samples generated for the TMB method was 500 for all analyses in this paper. The values of ERR_1 from Eq. 33 and ERR_2 from Eq. 34 for each gaging station using different sample sizes are listed in Table 3. This analysis considered the first N_p data points of the sample. Considering generalized parameter estimates for all three parameters resulted in decreasing values of ERR_1. This is true for all the cases, except for station 8030500 with $N_p = 40$. The reduction in parameter uncertainty (smaller values of ERR_1) was the most significant for small sample sizes.

Based upon the results (value of ERR_1 and ERR_2) listed in Table 3, the TMJ and TMB methods gave consistently better results than the other methods tested. This shows the importance of reducing the parameter uncertainty through methods such as the TMJ and TMB presented herein which considers uncertainties in the mean, standard deviation, and skewness, and which weigh the importance of sample and regional information.

It is interesting to note that for stations 8033500 and 8096500 the value of ERR_1 for $N_p = 40$ is larger than for $N_p = 20$ and about the same as for $N_p = 10$. This can be explained by examining the streamflow sequence of these two stations keeping in mind that the observations are drawn chronologically from the record. The annual maximum streamflow values observed between the first 20 yr and the first 40 yr are more or less in the high-flow region of the frequency curve determined by the total record. Then after the first 40 records, the flows observed are mostly in the low-flow region. This leads to the frequency curve having a better fit in the high-flow part for $N_p = 40$ than for $N_p = 20$, and the reverse situation is true in the intermediate- and low-flow parts. In other words, due to the criterion for comparison used and the realization of high- and then low-flows in the flow sequence, the peculiar results occured for stations 8033500 and 8096500. However, the main purpose of this study was to compare the capability of the different methods in their

TABLE 4.—Variances of Sample Statistics and Variances of Regional Estimates from Regression Equations

Variable (1)	Regional variance (2)	N_p = 10 J (3)	N_p = 10 B (4)	N_p = 20 J (5)	N_p = 20 B (6)	N_p = 40 J (7)	N_p = 40 B (8)
			(*a*) Station 8022500				
Var ($\bar{Y}$)	0.2397	0.0404[a]	0.0354[b]	0.0260	0.0289	0.0119	0.0112
$W_{\bar{Y}}$		0.8558[a]	0.8711[b]	0.9022	0.8924	0.9527	0.9552
Var (S)	0.0328	0.0110[a]	0.0087[b]	0.0047	0.0049	0.0039	0.0033
W_s		0.7497[a]	0.7899[b]	0.8739	0.8699	0.8948	0.9078
Var (G)	0.2581	0.3490[a]	0.2276[b]	0.1445	0.0842	0.0992	0.0341
W_G		0.4251[a]	0.5314[b]	0.6410	0.7540	0.7225	0.8833
			(*b*) Station 8030500				
Var ($\bar{Y}$)	0.2577	0.0418	0.0393	0.0140	0.0139	0.0066	0.0064
$W_{\bar{Y}}$		0.8604	0.8678	0.9484	0.9490	0.9750	0.9757
Var (S)	0.0183	0.0356	0.0226	0.0092	0.0079	0.0028	0.0025
W_s		0.3393	0.4475	0.6642	0.6985	0.8672	0.8784
Var (G)	0.2581	1.1961	0.2271	0.5132	0.1212	0.1075	0.0453
W_G		0.1775	0.4822	0.3346	0.6804	0.7060	0.8507
			(*c*) Station 8033500				
Var ($\bar{Y}$)	0.2248	0.0659	0.0635	0.0378	0.0383	0.0157	0.0170
$W_{\bar{Y}}$		0.7732	0.7824	0.8561	0.8544	0.9349	0.9296
Var (S)	0.0241	0.0394	0.0256	0.0178	0.0136	0.0074	0.0073
W_s		0.3800	0.4853	0.5752	0.6387	0.7654	0.7675
Var (G)	0.2581	0.6122	0.2465	0.1351	0.0634	0.0615	0.0168
W_G		0.7965	0.5115	0.6565	0.8027	0.8076	0.9390
			(*d*) Station 8057000				
Var ($\bar{Y}$)	0.2267	0.1102	0.0929	0.0499	0.0511	0.0189	0.0190
$W_{\bar{Y}}$		0.6729	0.7094	0.8195	0.8160	0.9233	0.9227
Var (S)	0.0276	0.2769	0.1339	0.0184	0.0156	0.0072	0.0066
W_s		0.0906	0.1708	0.5996	0.6395	0.7929	0.8067
Var (G)	0.2581	1.1941	0.4812	0.2481	0.1270	0.0974	0.0566
W_G		0.1777	0.3491	0.5098	0.6701	0.7259	0.8201
			(*e*) Station 8096500				
Var ($\bar{Y}$)	0.2573	0.0647	0.0580	0.0323	0.0328	0.0128	0.0120
$W_{\bar{Y}}$		0.7991	0.8160	0.8884	0.8871	0.9528	0.9555
Var (S)	0.0217	0.0188	0.0146	0.0084	0.0084	0.0042	0.0036
W_s		0.5358	0.5985	0.7207	0.7220	0.8375	0.8590
Var (G)	0.2581	0.3644	0.1868	0.1686	0.1020	0.0808	0.0348
W_G		0.4146	0.5801	0.6048	0.7168	0.7615	0.8813

[a]Jackknife to compute Var (θ_s).
[b]Bootstrap to compute Var (θ_s).

flow prediction based on the same situation, for instance, same amount of data available for analysis.

Tables 4*a* to 4*e* lists the variances of the sample statistics and the variances of the regional estimates from the regression equations. The variances of the sample statistics derived by the jackknife and bootstrap methods are listed. The weights for each parameter estimate, $W_{\bar{y}}$, W_s, and W_G are also listed for both the jackknife and bootstrap methods. As would be expected, the variances of the sample statistics decreased with an increasing number of data, resulting in larger weights for larger sample sizes. In other words, more weight is given to the sample statistics for larger sample sizes. The Var ($\bar{Y}$) and Var (S) show little variation between using the jackknife or bootstrap methods. However, the Var (G) computed by these two methods does show significant differences, resulting in W_G varying significantly between the two methods.

In all cases examined, the variance of regional mean, Var ($\bar{Y}_r$), was much larger than the variance of the sample statistics, Var ($\bar{Y}_s$). For example, considering station 8030500 Var ($\bar{Y}_r$) = 0.2577 whereas the Var ($\bar{Y}_s$) = 0.0418 was computed using the jackknife with N_p = 10. For the same station with N_p = 40, the Var ($\bar{Y}_s$) = 0.0066 was computed using the jackknife. The weights $W_{\bar{y}}$ for this station ranged from 0.8604–0.9757. The variances of the standard deviation showed somewhat differing results. Considering the same station, Var ($\bar{Y}_r$) = 0.0183 whereas the Var ($\bar{Y}_s$) = 0.0356, 0.0092, and 0.0028 for N_p = 10, 20, and 40 respectively were computed using the jackknife. The regional variance, Var (S_r), is smaller than the Var (S_s) for N_p = 10 by a factor of approximately two, whereas for N_p = 20, it is about 1/2. The weights W_s ranged from 0.3393 for N_p = 10 to 0.8672 for N_p = 40. These results illustrate that the standard deviation is quite sensitive to the sample size and the uncertainty involved in the standard deviation is significant, especially for small sample sizes. Keep in mind that the WRC method does not consider uncertainties due to the mean and standard deviation.

The variances of the skew derived from sample data, Var (G_s), varied significantly between those computed by the jackknife and bootstrap methods, resulting in significant differences between the weights, W_G. This is shown further in Table 4. The differences are smaller for larger sample sizes, as can be seen by examining Table 5*a*. For N_p = 10, W_G = 0.1775 computed by the jackknife as compared to W_G = 0.4822 computed by the bootstrap. For N_p = 40, W_G = 0.7060 computed by the jackknife as compared to W_G = 0.8507 computed by the bootstrap. Using the WRC method W_G = 0 for N_p = 10 and N_p = 20, giving no weight to the skew computed with the sample statistics. For N_p = 40, the weight, W_G, using the WRC method, would be 0.2. The 0.2 is considerably too low as compared to the results provided in Table 4 where the weights would range from approximately 0.7–0.94 depending upon the variance of the sample skew.

Summary and Conclusions

A methodology is introduced that can be used in hydrologic frequency analysis to reduce parameter uncertainty. The methodology consists of developing generalized values of the parameters (mean, standard deviation, and skewness) through the use of a weighting procedure between sample and regionalized

statistics. Weights are defined as a function of the variances of the sample parameters and regionalized parameters. The variances of the sample parameters are determined using two nonparametric statistical methods, i.e., the jackknife and the bootstrap. The variances of the regionalized parameters are determined through regression analysis. The ability of this methodology is illustrated using flood flow frequency data for the Southwestern United States.

Six different assessments concerning the weight between parameters derived from the sample and from the region in flood frequency analysis are considered. The performance of capability in flood prediction by each method is compared using five drainage basins in Texas and Louisiana. The accuracy of flood flow frequency prediction with and without considering the uncertainty in the mean and standard deviation is investigated. Two nonparametric statistical methods, i.e., jackknife and bootstrap, demonstrate their performance and capability in helping the hydrologists assess and reduce the uncertainties involved in many aspects of hydrologic problems.

Based on the results reported in this paper, the following general conclusions are made:

1. Using weighted values of parameters (mean, standard deviation, and skew) can improve the accuracy in flood frequency analysis. This is strongly suggested, especially when the sample size is small.
2. The weighting procedure should consider and be based on the variances resulting from sample estimates and regional estimates to minimize parameter uncertainty.
3. The jackknife and bootstrap methods provide a good means of computing the variances of sample estimates of parameters. Regression equations based on regional physiographical and meteorological variables can be used to compute variances of regional estimates of parameters.
4. Consideration of uncertainty involved in estimating the mean and standard deviation should be included in addition to the skew uncertainty, which can significantly decrease the error of prediction in flood flow frequency analysis.
5. The methodology presented herein for reducing parameter uncertainty was found to be far superior to the WRC method and others presented for the limited amount of testing that was performed.
6. The method presented herein can be applied to other types of hydrologic frequency analysis and is applicable for any type of distribution.
7. The method presented has a theoretical basis for determining weights between sample and regionalized data.

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

A = drainage area of river basin;
C_p = Mallows' C_p statistics;
D_i = Cook's distance of ith observation in regression analysis;
$E(\ )$ = expected value;
$\mathbf{e}$ = OLS residual vector;
ERR = error criterion;
$\hat{F}$ = empirical probability function;
$\hat{G}$ = weighted skew coefficient;
G_s = sample skew coefficient;
G_r = regional skew coefficient;
I = 10-yr, 24-h rainfall intensity;
k = number of parameters in regression model;
K_T = frequency factor for return period T in log-Pearson III flood frequency analysis;
L = main channel length;
M = total number of bootstrap samples generated;
N = total number of stream flow record used in flood frequency analysis;
N_p = number of observations;
N_t = mean annual number of thunderstorm days;
n = total number of data sets in regression analysis;
R = ratio of runoff to precipitation during month when annual maximum peak;
r^2 = square of multiple correlation coefficient;
$\bar{r}^2$ = adjusted square of multiple correlation coefficient;
S_r = regional standard deviation;
S_s = sample standard deviation;
S_l = main channel slope;
S_t = percentage of surface storage;
T = return period;
U = expected value of log-normal random deviates;
V = variance of log-normal random deviates;
$\mathrm{Var}(\ )$ = variance;
W_θ = weight between sample and regional estimates of parameter θ;
$\mathbf{X}$ = matrix of known independent variables in regression model;
$\mathbf{Y}$ = vector of dependent variables in regression model;
$\bar{Y}_s$ = sample mean of log-transformed streamflow records;
$\bar{Y}_r$ = regional mean of log-transformed streamflow records;
Y_i = log-transformed streamflow;
Y_i^* = log-transformed flow in bootstrap sample;
Z_T = observed flood magnitude;
$\hat{Z}_T$ = computed flood magnitude;
$\boldsymbol{\beta}$ = vector of regression parameters of regression model;
$\hat{\boldsymbol{\beta}}$ = OLS estimate of $\boldsymbol{\beta}$;
$\hat{\sigma}^2$ = variance of dependent variable in regression model;
$\hat{\sigma}^J$ = jackknife estimate of standard deviation;
$\hat{\theta}$ = weighted parameter estimate;
θ_s = sample parameter estimate; and
θ_r = regional parameter estimate.

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River Quality Model For Urban Stormwater Impacts

By Miguel A. Medina, Jr.,[1] M. ASCE, Wayne C. Huber,[2] James P. Heaney,[3] A. M. ASCE, and Richard Field[4]

Introduction

In a 1.67-sq mile (433·ha) urban watershed in Durham, N.C., it was found that the dissolved oxygen (DO) content of the receiving watercourse was independent of the degree of municipal waste treatment beyond secondary treatment during storm flows (2). Approximately one half of the stream miles in the United States are water quality limited and 30% of these stream segments are considered polluted to a certain degree with urban stormwater runoff (4). The implication is that, generally, secondary treatment of dry-weather wastewater flows is insufficient to meet desired receiving water quality standards: therefore, control of runoff pollution must be considered in areawide wastewater management plans and abatement programs. The results of a nationwide assessment of costs and related water quality impacts derived from nonpoint sources (6) were, among others, that:

1. Wet-weather flows represent at least 50% of the total wastewater flow from urban areas.
2. A generalized optimization model, assumning linear costs, predicted primary type facilities are preferable only up to a 10% level of biochemical oxygen

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[1]Asst. Prof. of Civ. Engrg., Duke Univ., Durham, N.C. 27706.
[2]Prof. of Environmental Engrg. Sciences, Univ. of Florida, Gainesville, Fla. 32601.
[3]Prof. of Environmental Engrg. Sciences, Univ. of Florida, Gainesville, Fla. 32601.
[4]Chf., Storm and Combined Sewer Sect., Municipal Environmental Research Lab., U.S. Environmental Protection Agency, Edison, N.J.

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demand (BOD) removal for wet-weather flows, with a secondary type facility preferable for higher levels of control.

3. On a national average basis using BOD removal as the effectiveness parameter, approx 39% of the combined sewer problem and 10% of the other wet-weather flows should be controlled before initiating tertiary treatment of point sources.

The 208 planning effort (Section 208, PL 92-500) established the need for various levels of urban water management analysis (4) to permit preliminary screening of municipal treatment alternatives. Four distinct levels of evaluation techniques, ranging from simple to complex procedures that can be integrated with one another, are summarized in the following:

Level I.—A desktop calculator, statistical analysis procedure, no electronic digital computer required.

University of Florida Methodology—permits the user to estimate the quantity and quality of urban runoff in the combined, storm and unsewered portions of each urban area.

Hydroscience, Inc. Methodology—use of a stormwater simulator and an analytical method based on probability distribution functions and statistical properties of rainfall, runoff, treatment and receiving water impact.

Level II.—A simplified continuous simulation model for planning and preliminary sizing of facilities, developed by Metcalf & Eddy, Inc.; or the computerized optimization version of University of Florida Methodology described in the foregoing.

Level III.—A refined continuous simulation model approach. Continuous hydrologic simulation models, e.g., STORM or continuous SWMM, which generate urban runoff hydrographs and pollutographs are followed by continuous receiving water impact analyses (Level III-Receiving model).

Continuous SWMM—University of Florida
STORM—Corps of Engineers by Water Resources Engineers, Inc.
Level III-Receiving—Duke University

Level IV.—A sophisticated single event simulation model, e.g., EPA SWMM, developed by Metcalf & Eddy, Inc., University of Florida, and Water Resources Engineers, Inc.

The first three levels essentially represent various degrees of planning detail with models running on hourly time steps for long simulation periods (years). Mathematical complexity and data requirements are kept at a minimum. At the third level, the methods used to generate storm runoff flows and pollutant mass rates or concentrations depend upon the continuous hydrologic simulation model selected by the user. Such techniques are well documented for two models that may be applied to both urban and nonurban watersheds: (1) The Hydrologic Engineering Center's Storage, Treatment, Overflow, Runoff Model

(STORM); and (2) the United States Environmental Protection Agency's Storm Water Management Model (SWMM) (8,9). The urban runoff flows and associated pollutant concentrations and mass rates, derived from storm events over the drainage area of interest, represent concurrent time series that are read by Level III-Receiving through the standard card reader devices, or from peripheral storage units (disk/tape/drum). Since the program has the built-in capability of accessing a user-created data set, any continuous hydrologic and water quality model may be considered (15). Detailed single-event models typically use short time steps (minutes) and short simulation times (hours). Their data requirements are usually substantial.

Model Overview

Since it is impractical, if not impossible, to meet stream standards all of the time it appears desirable to express allowable limits for various pollutants on a probabilistic or frequency basis. The approach guiding the development of Level III-Receiving was that the cost-effectiveness of various treatment alternatives can only be determined realistically by a continuous analysis of the frequency of violation of water quality standards. Such an analysis provides an approximation of the integrated system responses to the proposed treatment measures.

The problem of specific interest is to assess the separate and combined effects of the major urban sources of water pollution upon river quality. The relative impact of wastewater sources is appraised by estimating their effect on DO concentrations downstream from the urban area. It is of further interest to distinguish clearly between the relative pollutional impacts of storm sewer discharges and combined sewer overflows. An abstraction of the urban drainage system is presented in Fig. 1. The urban community served by a separate sewer system will convey stormwater runoff and municipal sewage through parallel conduits. The BOD concentration of the storm sewer runoff is mixed with the dry-weather flow (DWF) and accumulated sewer solids. An interceptor carries the sanitary design flow to the municipal sewage treatment plant. The combined sewer overflow is either given treatment or allowed to discharge directly to the receiving water. Since complete mixing is assumed, the BOD concentrations of the combined sewer overflow Q_c and the flow (DWFCMB) intercepted for treatment by the DWF facility are identical. Any desired degree of treatment may be imposed at both the DWF and the wet-weather flow (WWF) treatment plants. The concentration of the combined BOD inputs in the receiving water is given by

$$\mathrm{BOD}_m = \frac{\mathrm{BOD}_u Q_u + \mathrm{BOD}_d Q_d + \mathrm{BOD}_w Q_w}{Q_u + Q_d + Q_w} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which BOD_m = mixed BOD concentration in receiving water, in milligrams per liter; BOD_u = mixed BOD concentration from sources upstream of urban area, in milligrams per liter; BOD_d = BOD concentration of dry-weather flow treatment plant effluent, in milligrams per liter; BOD_w = BOD concentration of wet-weather flow treatment facility effluent, in milligrams per liter; Q_u = upstream flow, in cubic feet per second; Q_d = DWF treated effluent, in cubic

feet per second; and Q_w = WWF treated effluent, in cubic feet per second.

The BOD concentrations of the DWF and WWF treated effluents are given by:

$$BOD_d = \frac{[(BOD_f\,DWFSEP) + (BOD_c\,DWFCMB)](1 - R_d)}{DWFSEP + DWFCMB} \quad \ldots\ldots\ldots (2)$$

$$BOD_w = \frac{[(BOD_s Q_s) + (BOD_c Q_c)](1 - R_w)}{Q_s + Q_c} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

in which BOD_f = BOD concentration of municipal sewage, in milligrams per

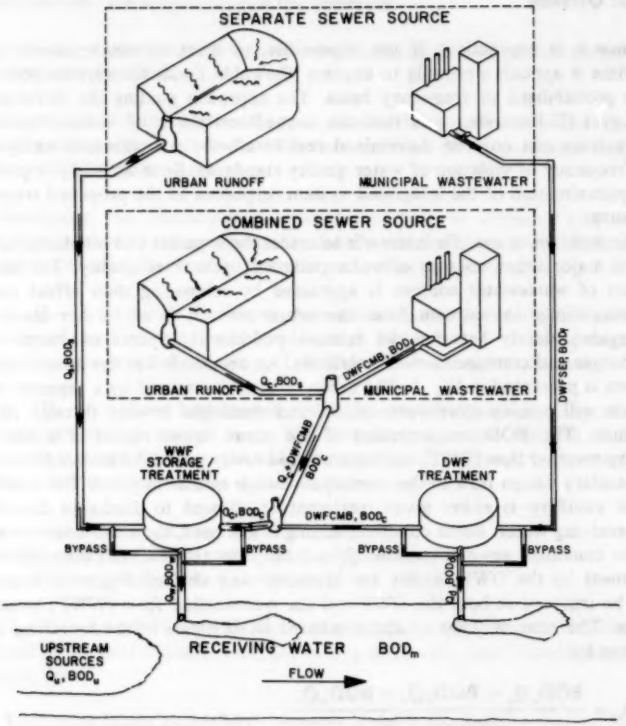

FIG. 1.—Abstraction of the Urban Drainage System

liter; BOD_c = mixed BOD concentration in the combined sewer, in milligrams per liter; BOD_s = BOD concentration of urban stormwater runoff, in milligrams per liter; DWFSEP = DWF contribution from separate sewer area, in cubic feet per second; DWFCMB = DWF contribution from combined sewer area,

in cubic feet per second; Q_s = urban runoff carried by the separate storm sewer, in cubic feet per second; Q_c = combined sewer flow, in cubic feet per second; R_d = fraction removal of BOD achieved by the DWF treatment facility, and R_w = fraction removal of BOD achieved by the WWF treatment facility.

The initial conditions of BOD in the river are defined by Eq. 1, and the hypothetical impact on the oxygen balance of the receiving stream is estimated by using simplified mathematical modeling approaches. The total hours of runoff-producing rainfall throughout the year are separated into storm events by defining a minimum interevent time. For a given storm event, the runoff and pollutant loads are summed and the critical DO deficit is estimated as a function of several stream parameters: (1) Temperature; (2) flow, (3) oxygen concentration; (4) deoxygenation and reaeration rates; (5) longitudinal dispersion; and (6) BOD concentrations. The minimum DO is calculated subsequently and a frequency analysis is performed. Stream velocity is computed as a function of the discharge and the time and distance to each critical deficit point are obtained for each event.

The options used for the simulations include:

1. Five inflow combinations of river flow plus: (a) DWF; (b) DWF + separate flow; (c) DWF + combined flow; (d) separate flow + combined flow; and (e) separate flow + combined flow; and (e) separate flow + combined flow + DWF.
2. Four DWF treatment rates (variable).
3. Three WWF treatment rates (variable).
4. Three fractions of measured upstream flow.

Item 4 is included as a model option to investigate whether the relative impact of urban stormwater runoff is significant in the upstream portions of river basins. This effect may be simulated by simply reducing the upstream flow to any desired fraction of its actual measured value. Thus, discharge into a dry river bed may be studied.

The impact of urban runoff on the quality of the receiving stream is evaluated in terms of: (1) Critical DO frequency curves, i.e., by the percent of time predicted minimum DO levels fall below a specified concentration; and (2) classical DO sag curves for each inflow combination. During periods of wet weather, the program performs computations on an hourly time step. Otherwise, a daily time step is used. An economic evaluation of various control strategies augments the decision-making capabilities of such an approach.

Event Definition

The basic approach to define a wet-weather event is to analyze the runoff time series and establish the minimum number of consecutive dry-weather hours (DWH) that separates independent storm events. The independence of these events is not defined in a strictly climatologic sense. The DWH refer to periods during which no runoff was produced.

The runoff time series is subjected to autocorrelation analysis. For hydrologic processes, it is practical to estimate the autocorrelation coefficients by an

open-series approach (5,18). Tolerance limits for a normal random time series which is circular and of lag 1 have been estimated for any percent probability level (1), and the technique has been extended for use with an open series for the general lag case (18). A plot of the serial correlation coefficients, $r(k)$, against the number of lags, k, is called a correlogram. Autocorrelation analysis is essentially a study of the behavior of the correlogram of the process under investigation (16). The model compares the value of $r(k)$ with the tolerance limit at the corresponding number of hourly lags, k. The *minimum interevent time* (MIT) which separates independent wet-weather events is defined as the minimum value of k, for which $r(k)$, is not significantly different from zero at a 95% probability level (15).

Effect on Receiving Waters

A simplified mathematical modeling approach is used in which critical deficits and resulting minimum DO concentrations are determined for a large number of waste input combinations, treatment schemes, and receiving water conditions. The development of a detailed and sophisticated model is not justified for the problem context: to provide adequate information on the relative effectiveness of various pollutant control strategies in achieving selected water quality standards. The basic theory of mathematical modeling of one-dimensional bodies of water is applied for the spectrum of natural systems from freshwater streams to tidal rivers. The approach is particularly advantageous for a limited data base on natural system geometry, hydrodynamic variables, and water. Assumptions typical of models limited for preliminary planning are made (10):

1. Temporal steady-state conditions prevail, in which all system parameters and inputs are constant with respect to time, however, a relatively short time step, 1 h, is used for simulation.
2. Natural system parameters (such as flow, velocity, hydraulic depth, deoxygenation and reaeration rates, and longitudinal dispersion) are spatially constant along the flow axis throughout each time step.
3. All waste inflows to the receiving body of water occur at one point.
4. The effects of various natural biological processes (algal photosynthesis and respiration, benthal stabilization) are incorporated into a background quality that is reflected by DO deficit (if none, by saturation) upstream from the waste inflow point. Any benthic buildup is incorporated into the BOD decay rate.
5. Waste treatment facilities operate at constant efficiencies, independent of hydraulic and organic loadings, for the entire period of simulation.

Some additional observations are appropriate with respect to the validity of simulating a transient situation with a steady state model such as Level III-Receiving:

1. It essentially averages pollutant loads and receiving stream conditions over an event duration, using an hourly time step.
2. It assumes that increased wet-weather flow will not cause sudden scour of benthal deposits sufficient to drive the DO to zero.
3. It assumes the time scale of the urban runoff event is short compared

to the time scale of the receiving stream response, i.e., time to critical DO deficit.

When the latter condition holds, transient pulses are greatly damped. Thus, the model is not suitable for use on small, *flashy* streams where most of the hydrograph consists of urban runoff. Level III-Receiving uses DO, because in spite of limitations on its implications on receiving water quality, it still represents the only parameter, besides bacteria, defined as a water quality *standard* in most states. For example, there are seldom any nutrient, sediment or toxic standards. Furthermore, these standards apply to dry-weather periods only. None of the regulatory agencies have established an *allowable frequency of violation* of water quality standards.

Oxygen Balance of Polluted Streams and Tidal Rivers.—In view of the modeling objectives, pollutant transport processes in these systems are approximated by the steady-state, one-dimensional version of the classical convective diffusion equation:

$$0 = \frac{\partial}{\partial x}\left[E\frac{\partial C}{\partial x} - \mathrm{UC}\right] \pm \Sigma S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

in which C = concentration of water quality parameter (pollutant), $\mathrm{M/L^3}$; $-E(\partial C/\partial x)$ = mass flux due to longitudinal dispersion along the flow axis, the x direction, $\mathrm{M/L^2T}$; UC = mass flux due to advection by the fluid containing the mass of pollutant, $\mathrm{M/L^2T}$; S = sources or sinks of the substance C, $\mathrm{M/L^3T}$; U = flow velocity, $\mathrm{L/T}$; and E = longitudinal dispersion coefficient, $\mathrm{L^2/T}$.

The equation assumes no diffusion of pollutants through the body of water boundaries (other than what may be included in the source-sink term) and is best suited to predict concentrations relatively far downstream from the point of waste injection. Since critical DO deficits usually occur some distance downstream from the waste source, Eq. 4 is adequate for such predictions. The main sources of dissolved oxygen in stream systems are *atmospheric reaeration* and oxygen production by *photosynthesis*. The major *sinks* include *carbonaceous oxygen demand* (CBOD), *nitrogenous oxygen demand* (NBOD), *benthal demand*, and respiration of aquatic plants. In the model, the effects of photosynthesis, respiration, and benthal demand are assumed to be incorporated into the measured upstream DO deficit. Field measurements of organic and ammonia nitrogen present in all wastewater inputs to receiving waters are seldom available, much less during runoff events. Thus, nitrogenous oxygen demand is currently neglected. Since it is desired to solve for the DO deficit and

$$\frac{\partial C}{\partial x} = -\frac{\partial D}{\partial x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Eq. 4 becomes:

$$E\frac{d^2D}{dx^2} - U\frac{dD}{dx} + K_1L_0e^{mx} - K_2D = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

in which $m = (U/2E)\{1 - \sqrt{1 + [(4K_1E)/U^2]}\}$ for $x \geq 0$; D = DO deficit, in milligrams per liter; E = longitudinal dispersion coefficient, in square feet

per hour; U = freshwater stream or tidal river velocity, in feet per hour; K_2 = atmospheric reaeration coefficient, per hour; K_1 = deoxygenation constant of carbonaceous BOD, per hour; and L_0 = remaining carbonaceous BOD concentration at $x = 0$, in milligrams per liter.

Critical Deficit and DO Levels.—The solution to Eq. 6 as a function of time since release is given by

$$D = \frac{L_0 K_1}{K_2 - K_1}\left(e^{jt} - \frac{s_1}{s_2}e^{gt}\right) + D_0 e^{gt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

in which D_0 = initial DO deficit, in milligrams per liter; $t = x/U$ = translational time, in hours; $j = [U^2/(2E)]\{1 - \sqrt{1 + [(4K_1E)/U^2]}\}$, per hour; $g = [U^2/(2E)]\{1 - \sqrt{1 + [(4K_2E)/U^2]}\}$, per hour; $s_1 = \sqrt{1 + [(4K_1E)/U^2]}$, dimensionless; and $s_2 = \sqrt{1 + [(4K_2E)/U^2]}$, dimensionless.

The time at which the maximum deficit occurs is obtained by taking the partial derivative of Eq. 7 with respect to time, setting the resulting equation to zero and solving for time. After simplification and convenient substitutions

$$t_c = \frac{1}{(j - g)} \ln\left[\frac{g}{j}\left(\frac{s_1}{s_2} - fR_0 + R_0\right)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

in which t_c = elapsed time at which the critical deficit occurs, in hours; f = self-purification ratio = K_2/K_1; and R_0 = ratio of the initial DO deficit, D_0, to the initial BOD, L_0, dimensionless.

Finally, the critical deficit is found by substituting the value of t_c given by Eq. 8 into Eq. 7:

$$D_c = \frac{L_0 K_1}{K_2 - K_1}\left[e^{jt_c} - \frac{s_1}{s_2}e^{gt_c}\right] + D_0 e^{gt_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

in which D_c = critical (maximum) deficit, in milligrams per liter.

The minimum DO level is calculated as

$$C_{min} = C_s - D_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

in which C_{min} = concentration of DO at maximum deficit, in milligrams per liter; and C_s = saturation concentration of DO, in milligrams per liter. The saturation concentration is determined from the regression relationship (17)

$$C_s = 14.652 - 0.41022\,T + 0.0079910\,T^2 - 0.000077774\,T^3 \quad \ldots\ldots\ldots\ldots (11)$$

in which T = water temperature, in degrees Celsius.

For freshwater streams, the advective flux is significantly larger than the mass flux due to longitudinal dispersion. In a tidal river, the advective and dispersive fluxes are both significant. However, it should be noted that even for large, deep rivers, the effect of dispersion generally cannot be neglected when the wastewater inputs are time variable (13,14). If the model user wishes to neglect the dispersive flux, the classical Streeter-Phelps formulations are then applied.

The Langbein and Durum (11) equation for the prediction of the reaeration coefficient was chosen because it is most closely related to subsequent procedures applied to obtain stream velocity and depth:

$$K_2 = 2.303 \left[3.3 \frac{U}{H^{1.33}} \right] \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (12)$$

in which K_2 = reaeration coefficient at 20° C, per day; U = stream velocity, in feet per second; and H = stream depth, in feet.

The problem lies in obtaining values of U and H, since the streamflow varies with time. In the absence of measurements, or if the data cannot be obtained in an expedient manner (as in the ensuing application to the Des Moines River), an approximation can be made (12) which uses strong correlations between velocity versus flow and depth versus flow, namely:

$$U = \alpha_1 Q^{\alpha_2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (13)$$

$$H = \beta_1 Q^{\beta_2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (14)$$

in which Q = streamflow, in cubic feet per second; and α_1, α_2, β_1, β_2 = regression coefficients. The model user also has the option of computing the deoxygenation coefficient, K_1, as a power function of water depth (10):

$$K_1 = \gamma_1 H^{\gamma_2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (15)$$

in which γ_1, γ_2 = regression coefficients. Temperature corrections are applied to carbonaceous BOD, deoxygenation and reaeration rate coefficients.

Application to Study Area

The city of Des Moines, Iowa is located near the confluence of the Des Moines River and the Raccoon River. It contains approx 200,000 out of the total population of 288,000 for the metropolitan area (3). The mean annual precipitation is 31.27 in. (795 mm) which is approximately equal to the United States average, and the average value for the state of Iowa. The urban area covers 49,000 acres (19,830 ha) of land which has gently rolling terrain. Most of the area, 45,000 acres (18,211 ha), is served by separate sewers, while 4,000 acres (1,619 ha) are served by combined sewers. Davis and Borchardt (3) conducted an extensive sampling program of combined sewer overflows, stormwater discharges, and surface waters in the metropolitan Des Moines area from March 1968–October 1969.

The autocorrelation function of hourly runoff events for Des Moines, Iowa is presented in Fig. 2. An essentially zero correlation (within 95% tolerance limits) between runoff events first occurs at a lag of approx 9 h, defining the minimum interevent time. The physical interpretation is that periods without runoff for at least 9 h separate uncorrelated, and therefore independent, wet-weather events. The hourly urban runoff and associated pollutant loads within each event (including DWF pollutant loads during DWH periods less than 9 h duration) are summed, average conditions are determined, and the model proceeds with the receiving water analysis.

Model calibration was preceded by calibration of the urban runoff BOD_5 loading rates for Des Moines, Iowa as computed by STORM. Model parameters were adjusted to obtain a fit between calculated and observed profiles of DO (*standard error of estimate* = 1.86 mg/L). These curves are shown in Fig. 3, along with other pertinent information, and correspond to a point 5.6 miles

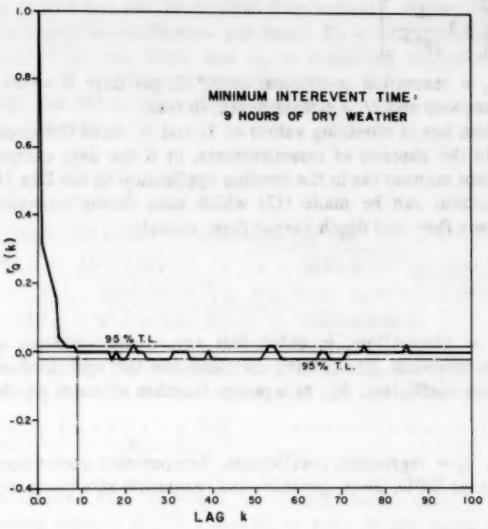

FIG. 2.—Autocorrelation Functions of Hourly Urban Runoff for Des Moines, Iowa, 1968

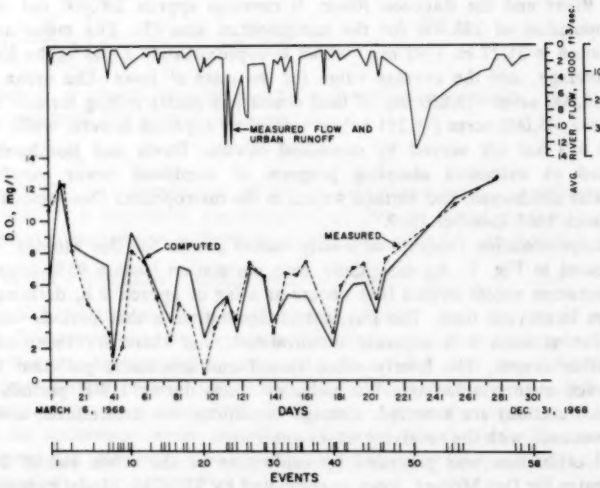

FIG. 3.—Application to Des Moines, Iowa. Measured and computed values of DO at 5.6 miles (9.0 km) downstream from confluence of Raccoon and Des Moines Rivers

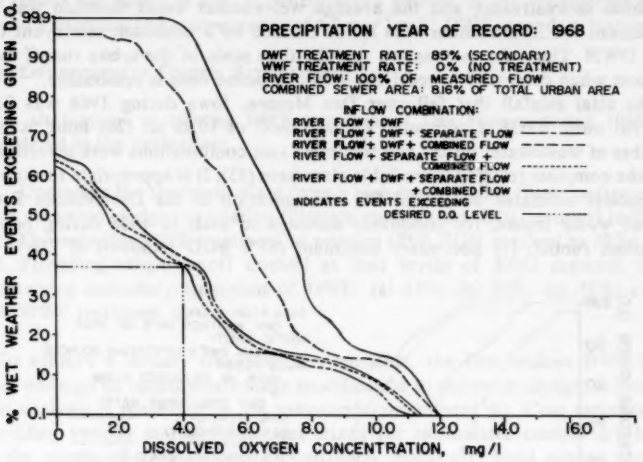

FIG. 4.—Minimum DO Frequency Curves for Existing Conditions in the Des Moines River

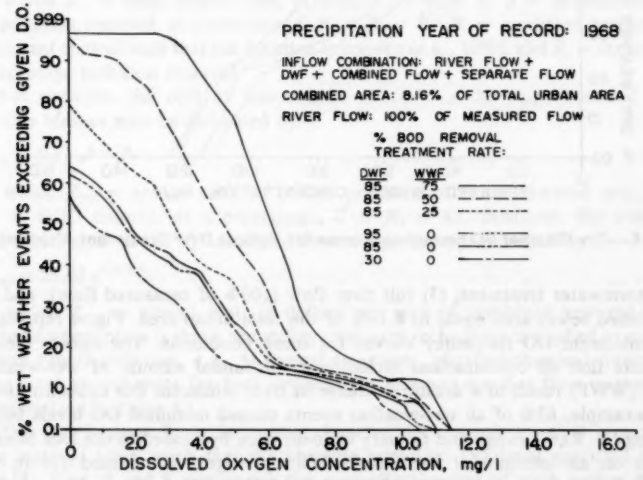

FIG. 5.—Minimum DO Frequency Curves for Various Treatment Alternatives

(9.0 km) downstream from the confluence of the Raccoon and Des Moines Rivers. The average time to maximum DO deficit in the stream was 32 h (about 40 miles downstream); and the average wet-weather event duration was 6 h (minimum = 1 h, maximum = 24 h), as defined by a minimum interevent time of 9 DWH. Thus, the assumption that the time scale of the urban runoff event is short when compared to receiving water response time is reasonable.

The total rainfall that fell over Des Moines, Iowa during 1968 was 27.59 in. (701 mm): STORM computed a total runoff of 10.28 in. (261 mm). A large number of wastewater inflow and treatment rate combinations were investigated and the complete results are available elsewhere (15). It is appropriate to examine the model estimates of critical DO concentration in the Des Moines River, for all waste inputs, for conditions assumed to exist in 1968 during periods of urban runoff: (1) Secondary treatment (85% BOD removal) of DWF; (2)

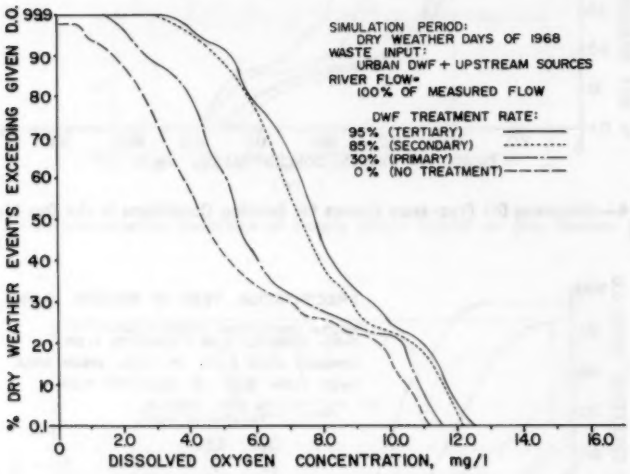

FIG. 6.—Dry-Weather DO Frequency Curves for Various DWF Treatment Alternatives

no stormwater treatment; (3) full river flow (100% of measured flow); and (4) combined sewer area equal to 8.16% of the total urban area. Fig. 4 represents the minimum DO frequency curves for these conditions. The curves clearly indicate that all combinations including a substantial amount of wet-weather flow (WWF) result in a drastic decrease in river minimum DO concentrations. For example, 63% of all wet-weather events caused minimum DO levels below 4.0 mg/L. Raw sewage and primary effluent were by-passed to the Des Moines River on an intermittent basis from January–August (accounted for in the simulation) due to construction of high-rate trickling filters.

The minimum DO frequency curves in Fig. 5 compare six treatment alternatives to reduce water pollution during periods of urban runoff. Even option three, with a small percentage of urban runoff treatment, is superior to all alternatives

controlling DWF only. For the dry-weather simulation period, upstream river flow was on the average 94% of total river flow, ranging from 82%–99.6%. The results are shown in Fig. 6. Ninety-seven percent of the dry-weather days exceed a minimum DO concentration of 4.0 mg/L with DWF secondary treatment.

Cost-Effectiveness of Control Alternatives

Six alternatives to existing DWF treatment in Des Moines during 1968 are considered in the evaluation:

1. Upgrading the treatment plant from a high-rate trickling filter configuration to an activated sludge-coagulation-filtration system (85% BOD removal to 95%).
2. Downgrading DWF treatment to primary (85% BOD removal to 30%).
3. Providing urban runoff control at four levels of BOD removal while maintaining secondary treatment of DWF: (a) 25%; (b) 50%; (c) 75%; or (d) 85% WWF treatment.

To achieve a tertiary treatment configuration, the Des Moines DWF plant must undergo an intermediate-stage modification to activated sludge. A detailed cost analysis is presented in the nationwide assessment (6). Cost estimates of providing various storage/treatment mixes for stormwater control are based on the results of a constrained optimization model (7). Total annual cost for the optimal solution can be approximated by functions of the form:

$$Z^* = ke^{\beta R_1} \quad \ldots\ldots\ldots\

TABLE 1.—Annual Costs for Control Alternatives

Alternative (1)	Total annual cost,[a] in dollars per year (2)
Dry weather[b]	
activated sludge-coagulation-filtration	3,507,000
high-rate trickling filter	1,843,000
primary	405,000
Wet-weather control,[c] (BOD removal as a percentage)	
25	816,000
50	2,682,000
75	9,293,000
85	15,479,000

[a]Includes amortized capital costs (20 yr, 8%, Engineering News-Record index 2200), operating and maintenance costs.

[b]For plant size 35.3 mgd (1.55 m^3/s).

[c]Based on 45,000 acres (18,211 ha) of storm sewer area; 4,000 acres (1,619 ha) of combined sewer area.

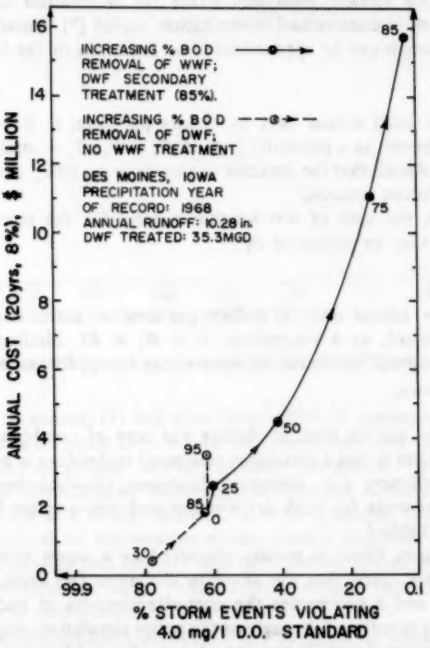

FIG. 7.—Cost Effectiveness of Control Alternatives during Periods of Urban Runoff

should be considered only after a secondary treatment technology of DWF has been achieved. However, beyond that level 25% and 50% WWF treatment become competitive with DWF tertiary treatment technology. It is clearly shown in Fig. 8 that, when the entire period of simulation (1 yr) is considered, 85% WWF treatment becomes asymptotic to the minimum number of violations that can be achieved, at a very high cost. Both 25% and 50% WWF treatment

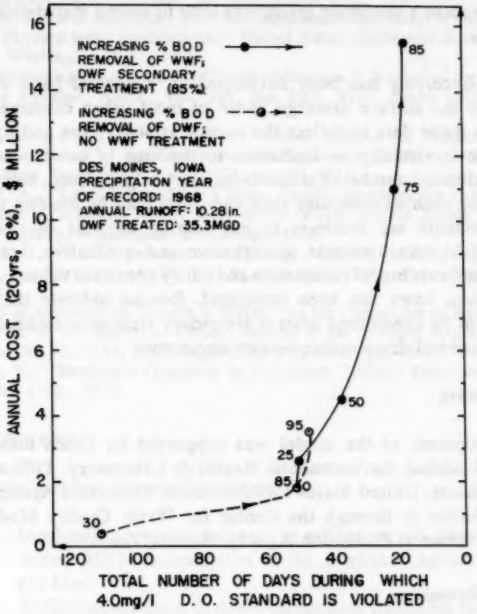

FIG. 8.—Cost Effectiveness of Control Alternatives during Entire Simulation

remain strong alternatives to higher than secondary treatment of DWF in relative cost-effectiveness.

Summary and Conclusions

A simplified river quality model has been developed to permit preliminary planning and screening of areawide urban wastewater treatment alternatives, in terms of frequency of violations and more traditional approaches such as DO profiles. It evaluates the stream response to the separate and combined effects of waste inputs from: (1) Upstream sources; (2) dry-weather urban sources; and (3) wet-weather urban sources. Among its capabilities are:

1. Level III-Receiving may be interfaced through peripheral storage devices

with various hourly, continuous urban catchment hydrologic simulation models.

2. A large number of wastewater inflow combinations, dry-weather flow and wet-weather flow treatment rates, and upstream flow conditions may be simulated. Thus, a comparative evaluation of control alternatives is possible in terms of their subsequent impact on receiving water quality.

3. Continuous analysis allows representation of water quality impacts due to the random occurrence and probabilistic nature of hydrologic phenomena.

4. It computes a minimum interevent time to define statistically independent storm events.

Level III-Receiving has been developed on a general basis so that it may be applied to the surface drainage phase of most urban catchments by simply changing the input data to reflect the particular study area and hydrologic time series. There is virtually no limitation to the size of catchment modeled. In theory, an unlimited number of storm events may be processed; however, practical considerations such as computer time and costs may be limiting to some users. Data requirements are common to engineering analysis of nonpoint source problems. Field measurements, quantitative and qualitative, are necessary to adequately calibrate model parameters and verify predicted values. An application to Des Moines, Iowa has been presented. Results indicate that wet-weather control should be considered after a secondary treatment technology has been achieved to control dry-weather wastewater inputs.

Acknowledgments

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Appendix II.—Notation

The following symbols are used in this paper:

BOD = biochemical oxygen demand, in milligrams per liter;
BOD_c = mixed BOD concentration in the combined sewer, in milligrams per liter;
BOD_d = BOD concentration of dry-weather flow treatment facility effluent, in milligrams per liter;
BOD_f = BOD concentration of municipal sewage, in milligrams per liter;
BOD_m = mixed BOD concentration in receiving water, in milligrams per liter;
BOD_s = BOD concentration of urban stormwater runoff, in milligrams per liter;
BOD_u = mixed BOD concentration from sources upstream of urban area, in milligrams per liter;
BOD_w = BOD concentration of treated wet-weather effluent, in milligrams per liter;
BOD_5 = standard BOD test, 5 days at 68° F (20° C), in milligrams per liter;
C = concentration of water quality parameter, M/L^3;
C_{min} = concentration of DO at maximum deficit, in milligrams per liter;
C_s = saturation concentration of DO, in milligrams per liter;
D = (DO) deficit = $C_s - C$, in milligrams per liter;
D_c = critical (maximum) deficit, in milligrams per liter;

D_u = DO deficit in receiving waters upstream of inflow point, in milligrams per liter;
D_0 = initial DO deficit, in milligrams per liter;
E = longitudinal dispersion coefficient, in square feet per second;
f = self-purification ratio, K_2/K_1;
H = stream depth, in feet;
K_1 = deoxygenation constant of carbonaceous BOD, per hour;
K_2 = atmospheric reaeration coefficient, per hour;
k = number of hourly lags;
k = coefficient;
L = Length;
L_0 = remaining carbonaceous BOD concentration, in milligrams per liter;
M = Mass;
Q = streamflow, in cubic feet per second;
Q_c = combined sewer flow, in cubic feet per second;
Q_d = DWF treated effluent, in cubic feet per second;
Q_s = urban runoff carried by the separate storm sewer, in cubic feet per second;
Q_w = wet-weather flow (WWF) treated effluent, in cubic feet per second;
R_d = fraction removal of BOD achieved by the DWF treatment facility;
R_w = fraction removal of BOD achieved by the WWF treatment facility;
R_0 = deficit load ratio = D_0/L_0;
R_1 = pollutant removal, as a percentage;
$\bar{R}_1$ = maximum pollutant removal, as a percentage;
$\underline{R}_1$ = minimum pollutant removal, as a percentage;
$r_Q(k)$ = sample estimate of lag-k autocorrelation coefficient for runoff;
S = sources and sinks of the substance C, M/L^3T;
T = Time;
T = stream temperature, in degree Celsius;
t_c = elapsed time at which critical deficit occurs, in hours or days;
U = flow velocity in stream, in feet per second;
x = distance downstream, in feet or miles;
Z_{CO} = annual cost, in dollars per acre of combined sewered area;
Z_{ST} = annual cost, in dollars per acre of storm sewered area; and
Z^* = total annual cost, in dollars per acre;
α_1, α_2 = regression coefficients;
β, β_1, β_2 = regression coefficients; and
γ_1, γ_2 = regression coefficients.

JOURNAL OF
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TECHNICAL NOTES

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4. All mathematics must be typewritten and special symbols must be properly identified. The letter symbols used must be defined where they first appear, in figures or text, and arranged alphabetically in an Appendix.—Notation.
5. Standard definitions and symbols must be used. Reference must be made to the lists published by the American National Standards Institute and to the *Authors' Guide to the Publications of ASCE*.
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9. Dual units, i.e., U.S. Customary followed by SI (International System) units in parentheses, should be used throughout the paper.

Improved Hourly Reservoir Operation Model

By Leonard Becker[1] and William W-G. Yeh,[2] M. ASCE

Introduction

The second writer et al. (3) described a real-time reservoir operation optimization procedure which could be applied to multiple facility situations involving nonlinear constraints and objectives. Application was made to the Central Valley Project (CVP) in California. The procedure essentially consists of Incremental Dynamic Programming with Successive Approximations (IDPSA) for which a required initial feasible policy is generated by an adaptive Linear Programming (LP) routine. This routine included an "ADJUST" procedure which operated on the LP output to exclude those releases which were known to cause rough operation of the turbines. The resulting policy consists of a set of releases which satisfied the hourly power requirements and other physical constraints, but were not necessarily optimal due to the linearization of the power generating curves. Use of the previous day's policy is often not possible, this use being previously excluded by the relatively irregular hourly power demands from day to day.

The CVP application was successful in that daily generated energy could be improved, and the required hourly generation schedule more adequately met than with the current operating procedures. However, improvements to the model have been suggested by a number of problems encountered in its use (1,2).

The first problem relates to the attainment of an initial feasible policy. The LP routine requires considerably more computer core for execution than does the IDPSA, and this requirement has led to low priority and large turnaround times on the Bureau of Reclamation CYBER computer; and large turnaround time is inconsistent with real-time operation.

The second problem involves the desirability of minimizing multiple start-ups and shutdowns of the generating units—i.e., the incorporation of unit scheduling into the optimization model. Such scheduling is not now present.

In general, the IDPSA procedure reduces dimensionality by decomposing a system into a number of subsystems, and optimizes each in serial fashion.

[1]Asst. Research Engr., School of Engrg., and Applied Sci., Univ. of California, Los Angeles, Calif. 90024.

[2]Prof., School of Engrg. and Applied Sci., Univ. of California, Los Angeles, Calif. 90024.

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This procedure may reach only a local optimum in the presence of a constraint ranging over several of the subsystems. The CVP hourly power demand is such a constraint.

The modifications described in the following greatly facilitate the attainment of a good initial feasible policy and eliminate the need for the LP, minimize multiple start-ups and shutdowns of the generating units, and result in better "optimal" solutions, although global optima cannot be guaranteed.

Theory

Removal of the hourly power demand requirement from the formal set of constraints makes possible a number of simple formulations whereby initial feasible policies can be obtained. The power demand requirement is incorporated into the IDPSA objective function as a "soft constraint" via a penalty function (4).

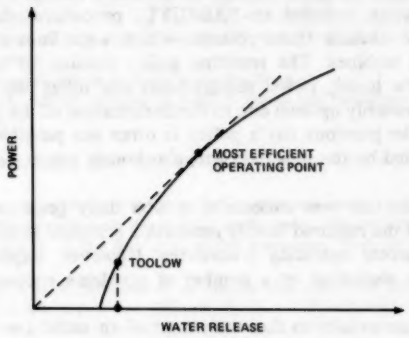

FIG. 1.—Turbogenerator Performance Curve

Let us define the penalty function P_1 by

$$P_1(G_i) = \min [-\text{Tol}_i, (G_i - D_i)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which G = total generated power; D = demanded power; Tol = tolerance in meeting a given quantity of demand; and i = hourly time period.

Incorporating the penalty function into the original objective function (3), and introducing a weighting factor W_1, the modified objective function becomes

$$\max \sum_{i=1}^{i=24} \{G_i + W_1 \min [-\text{Tol}_i, (G_i - D_i)]\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

If the generated power in any hour, G_i, is smaller than the power demand, D_i, by more than Tol_i, there will be a penalty proportional to the deficit and to the value assigned to W_1. In the absence of any other modification, the assignment of a relatively large value (e.g., 10) to W_1 would result in the later

stages of the IDPSA algorithm, in policies which are feasible with respect to the power demand requirement.

Since generator performance is nonlinear, particularly at the lower power values (a typical performance curve is given in Fig. 1), optimization is inhibited when the IDPSA procedure does not allow zero releases at each plant and at each time interval. IDPSA generally would not allow zero releases, in that fixed increments of the state variable (in this case the volumes of water available for possible release through each plant at each interval) are added to and subtracted from the states of the previous policy, and the probability of a zero release (zero difference between states in any two successive time intervals) is nil unless the previous policy had such a zero release. Releases close to zero would be rejected by the algorithm since water would be expended with no power generated, and an initial feasible policy would tend to keep its structure throughout the IDPSA "optimization."

A solution to this difficulty is offered by an adaptive procedure in incrementing from the last "optimal" policy to the trial policies which will be considered by the IDPSA for possible improvement of the objective function. At each time interval, either the positive or negative increments are modified to permit

TABLE 1.—Comparison of Results, Objective Function

Date (1)	Input policy* (2)	Final policy (3)
10-6-75	−28743	−15520
12-17-75	−37887	−13944
1-27-76	−31652	−15120

*Input policy is optimal policy for IDPSA algorithm of Ref. 3; input and final policies on common weights (W_1, W_2) basis.

zero releases in that time interval if the incremented states are within a specified difference from the states of the previous interval. The point in Fig. 1 labeled TOOLOW would represent the specified difference.

Multiple start-ups and shutdowns may be measured by the following penalty term

$$P_2 = \sum_{t=1}^{t\leq 24} \text{ABS}\,(G_t^f - G_{t-1}^f) \quad \ldots\ldots\ldots\

This objective function was used in the CVP application by assigning values of $W_1 = 10$ and $W_2 = 10$ for the first three IDPSA cycles (during which start-ups and shutdowns were minimized at the cost of some power deoptimization and power demand constraint violation) and values of $W_1 = 10$, $W_2 = 1$ for the next three IDPSA cycles (during which demand constraint violations were minimized). Optimization for the latter 3 cycles was performed with substantially

TABLE 2.—Comparison of Results, Dec. 17, 1975, CVP

	MEGAWATTS GENERATED												
	Shasta		Trinity		Folsom		Carr		Spring Creek		Total CVP*		Power demand, in megawatts
Hour	I	O	I	O	I	O	I	O	I	O	I	O	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	281	228	0	0	0	49	0	0	0	0	360	355	360
2	234	226	0	0	22	42	0	0	0	0	335	346	337
3	56	226	54	0	149	42	0	0	0	0	337	346	337
4	0	226	54	0	150	42	0	0	0	0	336	346	337
5	267	228	0	0	0	42	56	0	0	0	343	348	342
6	262	266	26	0	24	42	0	0	0	0	387	386	388
7	348	300	0	0	0	42	0	0	0	0	423	420	422
8	451	371	0	0	0	73	0	0	0	0	526	522	526
9	399	410	0	49	141	73	0	0	0	0	614	610	614
10	469	411	18	49	50	72	0	0	0	0	612	609	614
11	469	411	12	48	50	72	0	0	0	0	606	609	614
12	313	374	54	0	0	72	0	0	88	0	531	525	529
13	432	418	0	0	0	84	77	0	0	0	586	580	585
14	371	420	0	0	141	87	0	0	0	0	589	586	590
15	469	395	0	0	0	81	78	65	0	0	624	619	624
16	296	376	54	0	141	61	0	66	0	0	568	580	566
17	469	418	54	60	141	79	0	71	0	64	741	769	774
18	469	470	42	59	143	151	91	82	97	66	919	906	911
19	416	439	39	54	135	86	60	81	75	67	805	805	807
20	453	376	0	52	139	92	0	0	0	68	671	666	671
21	399	350	0	41	82	78	0	0	0	0	561	547	551
22	337	328	0	0	82	77	0	0	0	0	499	483	488
23	320	302	0	0	42	54	0	0	0	0	442	434	438
24	302	300	0	0	0	51	0	0	0	0	382	430	380
Total											12,797	12,825	12,805

*Includes Keswick and Nimbus outputs.

Note: Optimal policy of IDPSA in Ref. 3; I = input policy to modified IDPSA, in megawatts; O = output policy of modified IDPSA, in megawatts.

smaller values of the nominal state increments, in accordance with normal IDPSA methodology, and the unit commitment pattern obtained at the end of the third cycle was not generally disturbed. Convergence is established when there is no change in state for all hours during the optimization, which in turn implies that a local optimum has been reached. The smallest state increment used was 2.5 acre-ft (2982.5 m^3).

Comparison of Results

Release policies, reported for some typical CVP days (3), were compared with policies obtained by using the modified IDPSA. Table 1 shows the considerable improvements in the objective function, and Table 2 compares, in some detail for each CVP facility, the policies for one of the days. Table 2 includes Keswick and Nimbus regulating facilities which are approximately constant output in total CVP generation. The policies obtained by the use of the IDPSA algorithm described in Ref. 3 were initial policy inputs to the modified IDPSA. The megawatt tolerance on the power generation was taken as five for each hour.

In general, it would appear that the modified IDPSA allows a better "optimum" to be obtained than does the normal version. However, more extensive comparisons would be desirable to confirm this conclusion. Multiple start-ups and shutdowns of generating units are greatly decreased. Additionally, the IDPSA modifications facilitate the fabrication of an initial feasible policy since it is unnecessary that the initial policy satisfy the power demand each hour.

Acknowledgment

The research upon which this paper is based was supported by the National Science Foundation under Grant No. ENG 77-21232.

Appendix.—References

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DISCUSSION

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Two Centuries of Water Planning Methodology[a]

Discussion by Ellis L. Armstrong,[2] Hon. M. ASCE

The author has presented an interesting outline of his version of water planning methodology during the past two centuries, some of which is considered sound by the writer. However, there is a taint of the cynicism of an academician viewing his interpretation of the motivations in the "real" world. Generalizations which may be only partly or occasionally so, create a distorted overall view.

For example, the innenduoes in the definitions of planning in the first paragraph, do injustice to most professional engineers. The innenduoes are (italics provided): (1) *Demonstration that a predetermined solution* is economically feasible; (2) selection of the least costly of *several similar and mutually exclusive structural* solutions; (3) selection of the *least costly* alternative; (4) identifying *all possible reservoir sites* in a region and *attempting to find some use for each*; and (5) the *design of a specific* structure.

A predetermined solution isn't formulated in a vacuum, or by chicanery, or by sheer stupidity (it may be on occasion), but has come about by at least some degree of planning. Wide experience, education, and background often enable judgements to be made without the elaborate and often costly and sometimes worthless documentation that amateurs identify as planning. Many recent environmental impact statements which produce volumes of minutiae, much of which is irrevelant and insignificant, are examples of this type of documentation. The writer strongly supports intelligent planning that realistically and fully evaluates various options that will meet the defined needs, or that is necessary to define the needs, but it should be done with judgement and common sense as a means to an end, not the end itself.

The fourth definition of the original paper implies a cynical view of practicing engineers; and the second paragraph takes the same type of view of engineering schools and of the reasons for constructing projects. The concept that projects are built to "keep staffs busy" or will "establish a world record" is poppycock. All motivations are many faceted and there are shortcomings, but some credit should be given to engineering professionalism. The author's innuendoes certainly don't agree with the writer's viewpoint, or those he has observed in most of his colleagues in 45 yr in the public works action arena.

The author's statement that consideration of environmental factors is "relatively new" appears to be based on a narrow view of what an environment is. From the beginning, it has been the job of the civil engineer to utilize natural resources

[a]March, 1979, by Ray Linsley (Proc. Paper 14405).

[2]Adjunct Prof. of Civ. Engrg., Univ. of Utah, Salt Lake City, Utah 84112; also Adjunct Prof. of Civ. Engrg., Utah State Univ., Logan, Utah 84321; also Consulting Engr., Ellis L. Armstrong Assoc., 3709 Brockbank Dr., Salt Lake City, Utah 84117.

and adapt the environment so that man could survive and have a meaningful life. Of course, to do this most effectively as populations increase, requires a full understanding of how to work with and adapt natural conditions for the good of mankind, both short range and long range, and this is not easy. There have been mistakes made, of course, especially when viewed from today's affluent perspective. The definition of a "quality environment" is quite different in our affluent society than when most people were struggling to survive, or from the viewpoint of a college professor with tenure compared to those in our society struggling to escape the bonds of poverty.

The writer agrees that there isn't a "formal methodology" for dealing with environmental problems, as the author states. The issues are too complex and the extremists have created too much confusion. No doubt an "endangered" something or other can be found on every square mile in the country. The inference that engineers aren't concerned, is nonsense. What engineers are concerned about are reasonably balanced solutions to problems, including an intelligent consideration of environmental factors.

The statement that "because engineers seemed peculiarly irresponsive to this view (that people were concerned about the environment) planning teams are becoming multidisciplinary . . .," is superficial. Multidiscipline planning teams were organized, usually by engineers, to bring the knowledge and abilities of various disciplines to cooperatively work to resolve the complex issues of our society. While United States Commissioner of Public Roads in the 1950s, the writer was involved in organizing some of the first multidiscipline planning teams, and suggested in a speech to a conference of sociologists that it was high time they expand their analysis of what society has done wrong in the past, and contribute something by providing input in a positive way to the planning process.

In organizing the Western U.S. Water Plan Study (authorized by the Colorado River Basin Project Act of 1968), the writer, as United States Commissioner of Reclamation, insisted that it be done as a multidiscipline, multi-institutional undertaking, with full input from the various involved disciplines. This action was not unique.

One of the great shortcomings of many historians is that information in publications which they "scholarly" analyze, is too often extremist and twisted views of shortcomings, and very little appears regarding the positive accomplishments; thus evaluations are distorted. This was particularly apparent to the writer in preparing the 200 year history of public works in the United States (14).

The writer is in general agreement with the author's conclusion, especially the need to broaden and improve civil engineering education. In the writer's view, the civil engineer is unique in that the principle function is to put various parts of technology together into a working system that will best meet the needs of people. This places the civil engineer at the interface between technology and the average citizen. To properly fill this role requires much more than quantitative specialization. It may well be time for the civil engineering profession and society to seriously consider establishment of a "School of Civil Engineering," along with the present "School of Law" and the "School of Medicine" in our universities, as an improved way to meet today's increasingly complex challenges, especially in natural resourses, and particularly with water resources.

APPENDIX.—REFERENCE

14. *History of Public Works in the United States, 1776–1976*, Ellis L. Armstrong, ed., American Public Works Association, Chicago, Ill., 1976.

WATER RESOURCES PLANNING—HISTORICAL DEVELOPMENT[a]

Closure by Theodore M. Schad,[4] F. ASCE

The writer appreciates the discussions by Armstrong and Chaturvedi which amplify the writer's point that increasing participation in water resources planning by the Federal government has tended to reduce the initiative of the states. Although, as pointed out by Armstrong, the new analysis of water planning included in President Carter's "water policy initiatives" appears to have been formulated without an adequate appreciation or understanding of what has gone before, one salutary effect has been noted; the grants to the states for water resources planning have been increased from the $3,000,000 level that prevailed through fiscal year (FY) 1979 to $21,000,000 in FY 1980, and the administration has requested $30,000,000 for FY 1981. Whether this increase in state funding will lead to any change in the trend toward Federal domination of the water planning field remains to be seen.

Otherwise, very little progress is evident in the 4 yr, and tens of thousands of pages of water policy documents that have been produced since the paper was prepared. The President's "water policy initiatives," of course, have a one word answer to Chaturvedi's rhetorical question, "In view of increasing demands on water resources planning to meet the varying needs of environmental protection, how is it proposed to meet the growing needs of future water requirements at an economical and viable cost?" That word is "conservation." New horizons in water resources planning will have to be created to meet the challenges posed by future demands for water.

Errata.—The following corrections should be made to the original paper:

Page 12, paragraph 3, line 1: Should read "attempted to pass the ball' instead of "attempted to apss the ball"

Page 18, paragraph 1, line 9: Should read "which made its own report" instead of "which make its own report"

Page 24, Appendix, Ref. 19: Should be PB 211–921. instead of pp. 211–921.

Page 25, Appendix, Ref. 34: Should be January 30, 1961. instead of January 39, 1961.

[a]March, 1979, by Theodore M. Schad (Proc. Paper 14410).

[4]Deputy Executive Dir., Commission on Natural Resources, National Research Council, 2101 Constitution Ave., Washington, D.C. 20418.

Western Economic Development and Water Planning: Bureau of Reclamation[a]

Discussion by Ellis L. Armstrong,[5] Hon. M. ASCE

What could have been an important contribution to a review of water resource planning, in the writer's view, is distorted by apparent preconceived conclusions supported by superficial analysis and lack of understanding of what actually has occurred. For instance, the statement in the first paragraph, that "the outcome has often been disappointing" is highly prejudicial. This is not to suggest hypothetically, or even actually, that many outcomes could not have been better, especially when examined from our present affluent viewpoint. However, when one realistically views what has occurred, with full appreciation of the great difficulties of establishing water resource planning philosophies that have built the West, and enabled the nation to utilize the "vast worthless area" as characterized by many at the beginning of the 19th century, the outcome must be viewed with commendation.

The statement that planning by the Bureau of Reclamation was project oriented, and that planning prior to 1960 was limited primarily to project-specific engineering plans, suggests major shortcomings in the "historical review" on which this article is based. While congressional authorizations usually were for specific project developments, they generally evolved from an overall comprehensive planning and evaluation of an entire river basin or drainage area. One of the writer's first assignments in the Bureau of Reclamation in the 1930s was being involved in overall planning of the potential of the upper Colorado River Basin, and determining how specific developments fitted into the overall optimum. The writers comments don't come from a review of jejune, second-hand, shopworn statements; he was there and he was involved.

There may be a problem of the authors in understanding how a multipurpose water resource project is developed. Generally, projects can't be done economically on a piecemeal basis, although they are often developed in stages. The references to hydropower and municipal and industrial water as subsidizing irrigated agriculture seems narrow. Charges for both power and M & I water are generally lower than any alternative, real or imaginary. And putting the entire multipurpose uses into an overall optimum program is essential to make the most effective use of limited water resources.

Further, the view that the investments made by the government in the development of the West, could better have been made in Georgia, say, where visible dollar returns could be higher, and that, with the Western development,

[a]March, 1979, by John E. Keith, Keith Wilde, Jay C. Andersen, and Allen LeBaron (Proc. Paper 14416).

[5]Adjunct Prof. of Civ. Engrg., Univ. of Utah, Salt Lake City, Utah 84112; also Adjunct Prof. of Civ. Engrg., Utah State Univ., Logan, Utah 84321; also Consulting Engr., Ellis L. Armstrong Assoc., 3709 Brockbank Dr., Salt Lake City, Utah 84117.

the Georgia benefits were foregone, is not realistic. This presupposes a perfect input-output type of nationwide economic system which does not exist.

The cynical analysis that engineers are motivated only by expanding their technology and the use of their common technical skills, is nonsense. The authors appear to lack an appreciation of the professionalism and ethics that are an important part of the basic motivation of most engineers. The implications of the statement that "it is not surprising to find that Reclamation engineers have encouraged local water lobbyists and done their best to ignore rival techniques, such as ground water development" is childish. It appears the authors seem to have obtained their "scientific" information from subjective writings such as the Sierra Club's "Water Hustlers" article they quote, which has the familiar hallmakers of superficial, incomplete research, immature analysis, and aversion to objectivity.

Several other statements in the article such as ". . . ground water available in Salt Lake area is sufficient to provide for M & I uses . . ." are not valid statements and appear to be founded on hearsay and rumor which disregards the real physical and institutional world.

It appears from the authors' reference to the writer's "Wake Up America" speech, that they failed to read the speech carefully or to understand what was being said. This was a speech given at the National Limestone Producers Annual Convention in Washington, D.C. in January 1972, and was a warning concerning the proliferation of "instant experts" in educational institutions and government, who lacked understanding and appreciation of America's basic problems. The conjectures that the speech "amply demonstrates the Bureau's aversion to both economic efficiency and environmental constraints" are utter nonsense. It does just the opposite. Anything can be proved with bits and pieces of paragraphs and sentences taken out of context. The following paragraphs are quoted from the speech:

> The purpose of Government is to help people create opportunities to help themselves; not just provide handouts.
>
> To illustrate from the operations of my own agency, the Bureau of Reclamation, we have a two-year intensive study of the Reclamation program just completed by a firm of economists and related disciplines. (Their assignment was to objectively examine the facts and make their own conclusions). This study shows that our capital investment of about $6 billion made over the past 70 years, is now creating economic activity, over and above what would have occurred without the investment, of over $4 billion per year.
>
> Taxes generated by this activity totaled $1.1 billion in 1971; including $800 million in Federal internal revenue and over $300 million in state and local taxes. And in addition, most of the capital investment is being repaid in hard cash on schedule into the United States Treasury.
>
> "More than that, the investment has created a quality environment for man where none existed before.

In regard to environmental issues, the following paragraphs from the speech illustrate the writer's concern:

> It really isn't a question whether we want growth or not. The so-called "environmentalists," with their no-growth theories and their doomsday forecasts should come down out of the clouds. Growth is here for as long as our generation lives. Beyond that, hopefully, we can and will stabilize our population growth.
>
> So the question, as any good engineer would see it, is how best can we plan for this growth of the next few decades? How are we going to meet the needs of people?
>
> What we need is simple integrity, basic honesty, plain straightforwardness and an ability to reason together—to see each other's point of view. We need to nail down what has been accomplished and to move ahead.
>
> Now I have sounded off on environmental extremism. But don't think for a moment that I am unaware of environmental concerns and environmental needs. These problems are real and must be solved. But we must keep the problems and solutions in proper perspective. We must strive for balance.

This article amply demonstrates the shortcomings of analyzing the nation's problems from a narrow, technician-type perspective, without an overall understanding and objective comprehension of the past and the complexities of today's programs. There are no easy answers or magic solutions, but we must continually strive to improve.

Evaluation of Alternative Stormwater Detention Policies[a]

Discussion by James S. Jenks,[4] M. ASCE

The authors have examined the performance of detention basins designed to accommodate storms having return periods of 2 yr, 10 yr, and 100 yr. One of the conclusions is that ". . . use of one return period as the basis for a detention basin design policy does not lead to a design that reflects the intent

[a]September, 1979, by Gregory E. Kamedulski and Richard H. McCuen (Proc. Paper 14806).

[4]Principal Engr., Leeds, Hill and Jewett, Inc., Consulting Engrs., 1275 Market St., San Francisco, Calif. 94103.

of stormwater management," and "for other return periods the policies result in either over or underdesign." The authors do not describe a detention basin design policy which does reflect the intent of stormwater management.

The intent of stormwater management is to avoid or minimize adverse hydrological impacts that result from urbanization. From an economic viewpoint it makes little sense to spend more on works to avoid adverse impacts than the magnitude of damages associated with such impacts. From this viewpoint detention facilities should be designed so that the last incremental or marginal cost of the facility (including operation and maintenance costs) produces as much incremental or marginal benefit (reduction of damage). The facilities would then be of optimum size economically. If the facilities are larger than this optimum size, there would not be a corresponding increase in the benefit (reduction of damage) for the increased costs incurred. Obviously, optimum size would vary from place to place. In some instances it might correspond to a 10-yr storm design; in other instances it might correspond to a 50-yr or 100-yr storm design.

From a practical viewpoint, urbanizing areas are generally small economic units and it is not worthwhile to conduct a marginal cost-benefit calculation. Further, with the present state of the art it is difficult to quantify and evaluate damages downstream of a particular area that would result from urbanization, although in some instances, potential damage to bridges, water supply facilities or recreation may be readily identifiable.

To the writer's knowledge such a cost-benefit analysis has not been completed in the past. A worthwhile research project might be to ascertain proper sizing criteria in a number of case histories and from this develop guidelines for practicing engineers to follow.

It might be noted that the adverse impacts caused by increased rates of stormwater runoff from urbanizing areas is a nationwide problem. In California, the State Coastal Commission is also deeply concerned with this problem. The commission is especially concerned with associated increases in erosion and siltation in areas tributary to coastal lagoons. These lagoons have limited lives even under natural conditions and can be significantly affected by siltation. Accordingly, the commission has adopted the policy that peak rate of runoff from a developed area shall be no greater than peak flow rate under existing conditions. Detention basins are a proven method of achieving this policy. Since specific design criteria to implement the commission policy is now evolving, the authors' paper describing analysis of detention basin design policies is particularly timely.

Map Skew???[a]

Discussion by Krishan P. Singh,[2] M. ASCE

The United States Water Resources Council issued guidelines in their Bulletin 17a to promote a uniform, consistent, and accurate technique for flood-frequency analysis with the log Pearson type III distribution (2). The bulletin emphasizes the inaccuracies in the estimate of the third moment, or skew, and presents a map with iso-skew contours derived from the analyses of annual flood series from a number of gaging stations in each 1° quadrangle. The author has presented an alternative contour map assuming that the coefficient of skew varies with location parameters such as latitude and longitude. It is said to lower the standard error of estimate of skew from 0.623–0.529, a reduction of 15%. The results of regression analyses of skew with basin and stream factors are also presented. The author correctly concludes that the estimation of skew appears to be an area that needs further study.

Consider the 1° quadrangle bounded by latitude 39° and 40° and longitude 89° and 90°. The average skew coefficient is given as −0.66 for the six stations in this quadrangle in the map (2). The lowest five floods and highest five floods at four gaging stations in this quadrangle are given in Table 4 together with the information on the drainage area, number of years of record, and the mean, $\bar{x}$, standard deviation, s, skew coefficient, g, and the 100-yr flood, Q_{100}, obtained by applying log Pearson type III distribution to the annual flood series. Also included are the weighted skew, g_w, and the 100-yr flood when g_w is used instead of the sample skew, g. An inspection of the floods at the high and low ends of the ranked annual flood series shows that one or two very low floods at each of the four stations depart significantly from the trend of the rest of the data. These low floods occurred in 1953 or 1954, or both, the years with a drought frequency of about 1 in 75 yr. The following criterion, recommended in Bulletin 17a for evaluating low outliers, was applied

$$\left|\frac{x-\bar{x}}{s}\right| > \left[2.5 + 1.2\log\left(\frac{n}{10}\right)\right](1 - 0.4\,g_r) \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

in which x = the logarithm of the low flood perceived as an outlier; and g_r = the regional skew (which equals −0.4 for the quadrangle under consideration). For x to be a low outlier, the left-hand side (LHS) in Eq. 1 needs to be greater than the right hand side (RHS). The test values are:

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[a]September, 1979, by Richard H. McCuen (Proc. Paper 14840).

[2]Principal Hydro., Illinois State Water Survey Div., Illinois Inst. of Natural Resources, P.O. Box 232, Urbana, Ill. 61801.

Basin number	LHS	RHS
1	2.646	3.500
2	2.192	3.544
3	3.190	3.544
4	2.179	3.500

Thus, the criterion indicates no low outliers in the four annual flood series.

The writer has developed and computerized a simple methodology for modifying any perceived outliers so that they fit the trend of the rest of the data. The low outliers modified are underlined in Table 4 and their modified values are given in parentheses. The log Pearson type III distribution was applied to the four series after replacing the low outliers with corresponding modified values.

TABLE 4.—Results of Flood Frequency Analyses at Four Gaging Stations

No.	Item	Mean $\bar{x}$	Standard deviation s	Skew g	Q_{100} cfs
1	Flat Branch near Taylorville, IL., 05 574500, 276 sq mi, 27 years				
	Lowest 5 floods: 457 (1090), 660 (1360), 1770, 1850, 1860 cfs				
	Highest 5 floods: 13000, 9400, 8620, 7540, 7350 cfs				
	a) Observed sample	3.541	0.333	-0.822	12,940
	b) Observed sample with g_w	3.541	0.333	-0.411	16,370
	c) Series with 2 low outliers modified	3.567	0.276	-0.032	15,920
2	Spring Creek at Springfield, IL., 05 577500, 107 sq mi, 29 years				
	Lowest 5 floods: 217 (377), 225 (479), 639, 640, 700 cfs				
	Highest 5 floods: 6750, 5100, 4760, 4700, 3320 cfs				
	a) Observed sample	3.163	0.377	-0.291	9,110
	b) Observed sample with g_w	3.163	0.377	-0.394	8,510
	c) Series with 2 low outliers modified	3.183	0.338	0.187	10,390
3	Lake Fork near Cornland, IL., 05 579500, 214 sq mi, 29 years				
	Lowest 5 floods: 152 (432), 548, 680, 1000, 1010 cfs				
	Highest 5 floods: 6102, 4900, 4700, 4570, 4130 cfs				
	a) Observed sample	3.244	0.333	-0.961	6,050
	b) Observed sample with g_w	3.244	0.333	-0.430	8,170
	c) Series with 1 low outlier modified	3.260	0.289	-0.096	8,150
4	South Fork Sangamon River near Rochester, IL., 05 576000, 867 sq mi, 27 years				
	Lowest 5 floods: 971 (1210), 1230 (1570), 2120, 2150, 2330 cfs				
	Highest 5 floods: 18100, 14300, 11000, 11000, 9130 cfs				
	a) Observed sample	3.678	0.317	-0.331	21,740
	b) Observed sample with g_w	3.678	0.317	-0.398	20,980
	c) Series with 2 low outliers modified	3.685	0.302	-0.147	22,670

The values of the parameters and Q_{100} are given in Table 4. Some points of interest are:

1. The skew increases from −0.822, −0.291, −0.961, −0.331 to −0.032, 0.187, −0.096, and −0.147, respectively, after modification of outliers. The average skew for the four basins increases from −0.601 to −0.022.
2. The standard deviation decreases from 0.333, 0.377, 0.333, and 0.317 to 0.276, 0.338, 0.289, and 0.302, respectively. The average standard deviation decreases from 0.340–0.301.
3. The mean increases from 3.541, 3.163, 3.244, and 3.678 to 3.567, 3.183, 3.260, and 3.685, respectively. The average of the means increases from 3.406–3.424.
4. The estimate of Q_{100} from the flood series after modification of one or two low outliers increases by 4.3 to 31.7% over that without modification.

It is necessary to adjust the observed flood series for any outliers before using the distribution parameters for regionalization. Because of the significant interaction between the values of standard deviation and skew and because a relatively large increase in skew can be offset by a small decrease in standard deviation, regionalization of skew alone is open to question. A preliminary analysis indicates that when outliers are adjusted, the distribution parameters indicate correlation with basin and stream factors.

Water Supply Regionalization: A Critical Evaluation[a]

Closure by Robert M. Clark,[3] M. ASCE

The writer would like to thank Walski for his interest in the paper and for his important comments. Walski, quite correctly, points out that another aspect of regionalization is the case of population centers connected by pipelines crossing areas with few if any water users. He identifies some of the variables to be considered when calculating service costs and briefly discusses methodology (MAPS) available for making some of these cost equations.

The writer agrees with Walski that regionalization is a useful concept that may not prove cost effective in every situation. Systematic methodology such as presented by Walski and in the original paper should be used by planners for calculating the cost of regional water supply systems.

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[a]September, 1979, by Robert M. Clark (Proc. Paper 14842).

[3]Engrg. Systems Analyst, Drinking Water Research Div., Municipal Environmental Research Lab., U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

VOTER REACTION TO MULTIPLE-USE DRAINAGE PROJECTS[a]

Closure by Thomas N. Debo,[4] M. ASCE and James T. Williams[5]

The writers would like to thank L. A. Brown for his interest in the paper and for his comments. The discusser raised a very important point in his discussion that was not explained in the paper. The multiple-use approach to developing drainage projects must include uses that are needed and wanted in a particular area. The Echo Branch sub-basin is representative of an urban residential area and the multiple uses examined were uses that would appeal and were needed in this area. For other areas of the county, different uses would have to be combined with drainage projects that would appeal to the voters in those areas.

The survey results were only used to show the appeal of the multiple-use concept and not to conclude that the bond referendum would have been passed if parks and recreation projects had been combined with the proposed drainage projects. But when a bond issue is defeated by only 4% and a multiple-use proposal indicated that at least 33% of those voting against the original plan would vote yes on the multiple-use plan in the basin studied, one would think that the multiple-use plan would have a much better chance of voter approval.

WATER RESOURCES EDUCATION REQUIREMENTS OF ENGINEERING FIRM[b]

Closure by Alan H. Schultz,[4] F. ASCE and Richard A. Westmore,[5] M. ASCE

The writers wish to thank L. M. Snell for his interest in the paper, and also acknowledge the many others who have corresponded on the same subject.

The methods described by Snell for improving student engineers' skills in

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[a]September, 1979, by Thomas N. Debo and James T. Williams (Proc. Paper 14843).

[4]Asst. Prof. of City Planning, Coll. of Architecture, Georgia Inst. of Tech., Atlanta, Ga. 30332; also Pres., Debo and Assoc., Atlanta, Ga.

[5]Gra. City Planning Student, Coll. of Architecture, Georgia Inst. of Tech., Atlanta, Ga. 30332.

[b]September, 1979, by Alan H. Schultz and Richard A. Westmore (Proc. Paper 14858).

[4]Assoc., Harza Engrg. Co., 150 S. Wacker Dr., Chicago, Ill. 60606.

[5]Water Resources Engr., Harza Engrg. Co., 150 S. Wacker Dr., Chicago, Ill. 60606.

problem definition and communication are entirely consistent with the suggestions offered by the writers.

It is evident from the response to the paper that the problems described relate to engineering education on a broader scale than water resources, and requirements of engineering firms. The writers are of the opinion that the engineering educators and practitioners are therefore responsible for seeing that these needs are redressed.

Practical Aspects of Town Water Planning[a]

Errata

The following correction should be made to the original paper:

Page 163, paragraph 4 under the heading "Water Demand Projections," line 9 following "Thus, unplanned" insert from page 165—
Paragraph 1 under the heading "Digital Computer Diversion Analysis," line 3 beginning with "growth beyond a population . . ."
through
Paragraph 3 under the heading "Diversion Location," line 7 ending with "requires a 30 mgd (1.14×10^5 m^3/day)."

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[a]March, 1980, by Paul G. Fischer and Tsung Ting Chiang (Proc. Paper 15279).

Technical Papers

Original papers should be submitted in triplicate to the Manager of Technical and Professional Publications, ASCE, 345 East 47th Street, New York, N.Y. 10017. Authors must indicate the Technical Division or Council, Technical Committee, Subcommittee, and Task Committee (if any) to which the paper should be referred. Those who are planning to submit material will expedite the review and publication procedures by complying with the following basic requirements:

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8. Tables should be typed (an original ribbon copy and two duplicates) on one side of 8-1/2-in. (220-mm) by 11-in. (280-mm) paper. An explanation of each table must appear in the text.

9. References cited in text should be arranged in alphabetical order in an appendix at the end of the paper, or preceding the Appendix.—Notation, as an Appendix.—References.

10. A list of key words and an information retrieval abstract of 175 words should be provided with each paper.

11. A summary of approximately 40 words must accompany the paper.

12. A set of conclusions must end the paper.

13. Dual units, i.e., U.S. Customary followed by SI (International System) units in parentheses, should be used throughout the paper.

14. A practical applications section should be included also, if appropriate.